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ÉVALUATION ENVIRONNEMENTALE DES CONSÉQUENCES DE LA DÉCARBONISATION DES SERVICES ÉNERGÉTIQUES

EVALUATING ENVIRONMENTAL CONSEQUENCES OF DECARBONISING ENERGY SERVICES

Thèse de doctorat
Spécialité: génie civil

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RESUME

Les services énergétiques sont essentiels au bien-être humain, mais l'utilisation de combustibles fossiles pour répondre à la demande énergétique compromet les moyens de subsistance des générations futures et des écosystèmes, par le réchauffement climatique et d'autres menaces. Il est donc urgent de transformer le système énergétique existant. Cependant, cette transformation peut créer des problèmes imprévus si elle n'est pas planifiée de manière cohérente et complète. Plusieurs plans de transition énergétique reposent sur des modèles d'optimisation des systèmes énergétiques (MOSE), mais ces modèles sont peu adaptés pour évaluer les facteurs de stress environnementaux et leurs effets, et ils adoptent des représentations trop simplistes des systèmes de production. L'hypothèse de base de cette thèse est qu'une approche combinant les MOSE et l'analyse du cycle de vie (ACV) peut permettre de surmonter les limites des MOSE, en aidant à éviter des imprévus dans les politiques de réduction de gaz à effet de serre.

Cette thèse donne un aperçu des limites des approches existantes reliant MOSE et ACV et met en œuvre une méthodologie possible pour les surmonter. Plusieurs questions liées à la transition énergétique au Québec sont évaluées à l'aide d'un modèle TIMES (NATEM) pour la province de Québec. Le scénario de modélisation des conséquences des objectifs de réduction des gaz à effet de serre (GES) est ensuite évalué selon une perspective de cycle de vie. Pour relier les deux modèles, un ensemble de fonctions et de procédures est codé dans un langage open source (Python), qui peut être réutilisé dans d'autres évaluations.

Les résultats montrent que seul un nombre relativement restreint de processus est à l'origine des changements dans la quantité de GES. Cette observation est utilisée pour simplifier la liaison entre les modèles TIMES et ACV. L'évaluation intégrée MOSE-ACV appliquée au Québec indique que les politiques de réduction de GES peuvent réduire les impacts sur la santé humaine et la biodiversité. Cette réduction d'impacts est due à la mitigation du changement climatique, mais également à d'autres mécanismes de cause à effet tels que la réduction de la pénurie d'eau et de la contamination par les métaux. De plus, la liaison des MOSE avec des modèles de simulation énergétique de bâtiments suggère que des bâtiments mieux isolés réduiraient les coûts totaux de réduction de GES. L'introduction de technologies à faibles émissions de carbone pourrait augmenter les coûts des services énergétiques de 20%, mais ces coûts pourraient être considérablement réduits grâce à des mesures axées sur la demande énergétique.

Les MOSE offrent une perspective intéressante, mais limitée, pour planifier les transitions énergétiques. La liaison des MOSE avec ACV est une approche viable pour donner une vue plus complète de l'importance relative des mécanismes qui affectent la santé humaine et la biodiversité. L'évaluation intégrée est un outil puissant pour analyser une large gamme de problèmes liés aux transitions énergétiques. Comprendre les hypothèses et principes sous-jacents des modèles est également important pour interpréter les résultats.

Pour faciliter ce type d'analyse, les chercheurs doivent faciliter la réutilisation de leurs travaux, en convenant des formats de sortie, en documentant le code sous-jacent aux analyses et en fournissant des outils pour intégrer les modèles. À cette fin, les outils open-source scriptables sont extrêmement utiles. Cette thèse tente de faire un pas en avant dans cette direction.

Mots clés : analyse de cycle de vie, energie, TIMES, MARKAL, NATEM,

SUMMARY

The services provided by energy commodities are essential for human wellbeing but the reliance on fossil-fuels is jeopardising the livelihood of future generations and ecosystems, through global warming and other cause-effect pathways. There is an urgent need to transform the energy system, but this transformation may create unforeseen problems if not planned comprehensively. Many energy transitions plans rely on energy system optimisation models (ESOM), but these models are ill-prepared to evaluate the range of environmental stressors and their effects, and have oversimplified representations of production systems. An integrative approach combining ESOMs with life cycle assessment (LCA) can overcome the limitations of ESOMs, helping to avoid the 'backfire' of mitigation policies.

This thesis gives an overview of the limitations of existing approaches linking ESOMs and LCA and implements a novel approach to overcome them. Several questions related to the energy transition in the province of Quebec (Canada) are assessed with the North American TIMES Energy Model (NATEM). The main scenario investigated, modelling the consequences of greenhouse gas (GHG) mitigation targets, is assessed from a life cycle perspective. To link both the optimization and the LCA models, a set of functions and procedures are encoded in an open-source software, that can be reused in other assessments.

Results show that just a relatively narrow number of processes drive the changes in GHG, and this feature can be used to simplify the linking between TIMES and LCA models. The integrated ESOM-LCA assessment applied to Quebec indicates that global warming (GW) mitigation policies would reduce impacts on human health and biodiversity. This reduced impact is driven by reduced climate change but also other cause-effect mechanisms such as reduced water scarcity and metal contamination. Additionally, full-year building simulations of Quebec detached houses introduced as new technological options in NATEM suggest that better insulated buildings would reduce the total costs of GW mitigation. The introduction of low-carbon technologies could raise the costs of energy services by 20% but these costs could be substantially lowered with demand-side measures.

ESOMs provide an interesting but limited perspective to plan energy transitions. The softlink of ESOMs with LCA is a viable approach to give a more comprehensive view of relative importance of cause-effect pathways affecting human health and biodiversity. The integrated assessment is a powerful tool to analyse a wide range of issues related to the needed energy transitions. Understanding the underlying assumptions and principles of models is also important to interpret and design assessments.

To facilitate this kind of analysis, researchers should facilitate the reusability of their works, agreeing on output formats, documenting the code underlying the analyses, and providing tools to integrate models. To this end, scriptable open-source software tools are extremely useful. This thesis attempts to put a step forward in this direction.

“[…] open your eyes and look unblinkingly at the world as it really is; be astonished by the beauty and horrified at the unnecessary suffering all around; dive into the wreckage and swim as hard as possible toward a distant and indistinct shore; doubt that your efforts made enough difference, and rethink, recalibrate, look again, link arms with others across the globe, and dive in once more."

William Ayers,

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LIST OF ACRONYMS

ALCA: attributional life cycle assessment

CF : characterisation factor

CLCA: consequential life cycle assessment

ESOM: energy system optimisation model

GHG : greenhouse gas

GW : global warming

IAM: integrated assessment model

IEA: international energy agency

LCA: life cycle assessment

LCI: life cycle inventory

NATEM: North America TIMES Energy Model

RES: reference energy system

LIST OF SCIENTIFIC COMMUNICATIONS

The research during the thesis has resulted in a number of publications and oral presentations. It has also facilitated several publications where either I am not the first author, or they are part of related but adjacent research.

Type	Reference
Submitted article	Astudillo MF, Vaillancourt K, Pineau P-O, Amor M Ben (under review) Environmental impact of deep decarbonisation of energy services. Nature Sustainability
Published article	Astudillo MF, Vaillancourt K, Pineau P-O, Amor B (2017) Can the household sector reduce global warming mitigation costs? sensitivity to key parameters in a TIMES techno-economic energy model. Appl Energy 205:486–498.
Published article	Astudillo, MF, Treyer, K., Bauer, C., Pineau, P.-O., Amor, M. Ben, 2017. Life cycle inventories of electricity supply through the lens of data quality: exploring challenges and opportunities. Int. J. Life Cycle Assess. 3, 374–386. https://doi.org/10.1007/s11367-016-1163-0
Published book chapter	Astudillo MF, Vaillancourt K, Pineau P-O, Amor B (2018) Integrating energy system models in life cycle management. In: Benetto E (ed) Designing sustainable technologies, products and policies. Springer Nature,
Published book chapter	Astudillo MF, Treyer K, Bauer C, Amor M Ben (2015) Exploring Challenges and Opportunities of Life Cycle Management in the Electricity Sector. In: Sonnemann G, Margni M (eds) Life cycle management, Springer, Heildelberg, pp 295–306
Oral presentation	Astudillo MF, Vaillancourt K, Pineau P, Amor B (2017) Integrating energy system models into consequential LCA. In: Setac Brussels 2017. Brussels,
Oral presentation	Astudillo MF, Vaillancourt K, Pineau P-O, Amor B (2017) Simplifying the integration of energy system models and LCA. In: LCM 2017. Luxembourg,
Oral presentation	Astudillo MF, Vaillancourt K, Pineau P-O, Amor B (2017) Rethinking the integration of energy system and life cycle assessment models. In: LCA XVII conference. Portsmouth, NH, October 2-6,
Published article	Astudillo MF, Azarijafari H (2018) Estimating the global warming emissions of the LCAXVII conference : connecting flights matter. Int J Life Cycle Assess 23:1512–1516.
Published article	Kuczenski B, Marvuglia A, Astudillo MF, et al (2018) LCA capability roadmap product system model description and revision. Int J Life Cycle Assess.
Published article	Pedinotti-castelle M, Astudillo MF, Pineau P-O, Amor M Ben (2019) Is the environmental opportunity of retrofitting the residential sector worth the life cycle cost? A consequential assessment of a typical house in Quebec. Renew Sustain Energy Rev 101:428–439.

CHAPTER 1 INTRODUCTION

1.1 Energy and environmental damage

Societies rely on energy commodities to fulfil their day to day needs, from transport and heating to the variety of services provided by electricity. During the last century, humankind has sharply increased their consumption of energy, improving living conditions for many, but also leading to large environmental damage (Smil 2004). For instance, nearly two-thirds of global greenhouse gas (GHG) emissions come from the energy sector.

Profound changes in the energy system are required to limit the harmful effects of global warming, and energy system optimisation models (ESOM) are at the core of global warming (GW) mitigation planning efforts (Pauliuk et al. 2017). These models help to design cost-optimal mitigation strategies, comparing technologies that deliver similar services. Well-known examples include global integrated assessment models (IAMs), but ESOMs are also used to design national or provincial energy transitions. Strategies often rely on higher levels of electrification and "decarbonisation" of electricity supply. However, the provision of energy services[1] is also associated with other harmful consequences like water scarcity or ocean acidification, that have the potential to jeopardise human wellbeing further and are not consistently addressed in ESOM.

Life cycle assessment (LCA) methods have gained traction in recent years to evaluate the potential effects on the environment of goods and services comprehensively. Life cycle inventories (LCI) include thousands of substances which are aggregated into indicators using impact assessment methods. These methods include many cause-effect pathways, from ocean acidification to particulate matter formation, and they can quantify potential effects on human health or ecosystems. LCA helps to analyse production systems systematically and find ways to reduce their impact. LCA has been instrumental to detect burden shifting, for example, in the case of first-generation biofuels (Hellweg and Milà i Canals 2014). Biofuels were at first considered as a benign option, but this technological approach "backfired" when other environmental mechanisms were considered (Hellweg and Milà i Canals 2014). "Indirect" land use change illustrates the importance of considering market-mediated mechanisms in decision making (Lapola et al. 2010; Creutzig et al. 2012). In LCA market-mediated effects are assessed using the consequential LCA approach (CLCA), which attempts to model the effects of changes in a production system. CLCA differs from the more common Attributional LCA (ALCA), which attempts to characterise the impact of a given product system. However, to date, the attempts to combine ESOM and LCA have focused on ALCA (Astudillo et al. 2018).

Models can be hard-linked (i.e. model interaction is controlled by software) or soft-linked (passing of information is controlled by users) (Wene 1996). Softlinking has the advantage of practicality, transparency and learning, and it is the starting point for linking models based on different

[1] Energy services are the ends for which the energy system provides its means. Examples include the transport, household thermal comfort, or lighting. The energy system encompasses all the components related to the production, conversion, and use of energy.

approaches (Wene 1996). The field is not mature enough for hard-linked models and this thesis opts for soft-linking TIMES and LCA models.

1.2 The energy transition in Quebec

This thesis analyses the energy transition of Quebec as a case study of how and why to integrate ESOM and LCA. Quebec is the second most populated province of Canada. Sparsely populated and with vast hydropower resources, most of its citizens live in humid continental climatic zone. Quebec aims to reduce GHG by 80% by 2050, which would mean emissions per capita in line with the Paris agreement. However, with 195 GJ of energy per capita in 2016 (Whitmore and Pineau 2018), it nearly quadruples the average per-capita energy consumption in the world, which strongly suggests there are opportunities for energy efficiency (Whitmore and Pineau 2018). The energy consumption is roughly equally divided between industry, transport and buildings (Whitmore and Pineau 2018).

On the supply side, the most relevant sector is electricity production, since it is vital in GW mitigation efforts (Astudillo et al. 2017a), and Quebec is a powerhouse of renewable electricity and historically a net exporter. Most of the electricity is produced in hydropower plants of the state-owned utility Hydro-Quebec, while all hydrocarbons are imported. However, building new hydropower plants is increasingly expensive, and their life-cycle GHG are rarely considered. Wind or solar are increasingly used around the world, but their intermittency may be an issue. The local government subsidises electricity from biomass residues, but there may be better ways to use this abundant local resource. Which approach would be the cheapest way to expand low-carbon electricity in Quebec remains unclear.

The household sector has clear potential for improvement. Around half of the total electricity production is consumed in buildings, mostly for heating purposes. Heating is also responsible for up to 50% of the peak electricity demand in winter. Most of the houses are heated using resistive heating systems, which transform a very versatile energy vector into low-temperature heat, the most 'degraded' one[2]. The use of resistive heating systems is affordable because households pay do not pay electricity at its marginal costs[3]. The pricing policy incentivises an 'inefficient' use of resources, incentivising household electricity consumption at the expense of other uses (Pineau 2009). Considering the marginal costs of energy supply would clarify which technologies help to bring down societal costs.

Another sector of interest is road transport. It is the largest consumer of fossil fuel products, and the largest emitter of GHG (Whitmore and Pineau 2018). Road freight and passenger transport are the largest consumers, followed by air transport (Whitmore and Pineau 2018). Regional energy policies foresee the use of natural gas powertrains in trucks as the strategy to reduce GHG (Govt. of Quebec 2016), although reference reports highlight that when life-cycle emissions are

[2] In thermodynamic terms, using electricity to generate heat would be a net loss of 'capacity to do work' (exergy).
[3] According to microeconomic principles goods should be priced at their marginal cost (i.e. the cost of producing the last unit of a good to be *efficient*. Efficient in this context means that society is operating in the 'utility' possibility frontier (Dorman 2014).

considered, emission reductions of gas-conversion are minor (IEA 2017). International organisms highlight natural gas is only an intermediate solution for freight transport (IEA 2017) and policies not looking in the long-term could result in stranded assets that difficult energy transitions (Moultak et al. 2017). The regional energy policy considers also taking energy consumption *into consideration* in urban planning, although it is unclear how. At national level, studies considering alternative urban developments have shown substantially lower transition costs (Trottier energy futures project 2016), which may also apply to Quebec. In sum, bringing a long-term, economic approach, combined with a life-cycle assessment could be very useful for local energy policies.

1.3 Thesis structure

Chapter 2 summarises the state of the art on the integration of ESOM's and LCA, starting by a brief description of both fields. It is built substantially on chapters 3 and 4 and some elements of chapter 6. The chapter ends with the research questions and outlines the expected original contributions of the research.

Chapter 3 reviews challenges and opportunities to improve LCIs of electricity supply from a data quality perspective. Electricity warrants special attention to energy transitions because it is pivotal in decarbonisation scenarios. It also has special features, such as our limited capacity to store it, that requires particular modelling. The chapter was published as an article in *The International Journal of Life Cycle Assessment*.

Chapter 4 reviews the challenges of integrating ESOM and LCA. It focuses on past attempts to combine models from the TIMES framework, among the most widely used ESOM (Pfenninger et al. 2014). It identifies the mapping of technologies (i.e. the identification of equivalent processes between two models) as a critical problem to link large ESOM and LCA. The chapter was published in the book *Designing sustainable technologies products and policies*. Both chapter 3 and 4 are a review of the state of the art of the integration of ESOM and LCA.

Chapter 5 uses a version of NATEM (North America TIMES Energy Model) to create scenarios of the energy transition in Quebec. The study concentrates on the opportunities of technological and demand transformations in the household sector. The study was published in the journal *Applied Energy*.

Chapter 6 improves the scenarios of chapter 5 updating the modelling of the transport sector, The most significant contributor to GHG in Quebec. The updated NATEM model is used to assess the potential consequences of global warming mitigation strategy compatible with the 1.5°C target. The chapter details the software created to integrate both modelling approaches. The manuscript was submitted for publication to the journal *Nature Sustainability*.

Chapter 7 summarises the conclusions of the integration exercise and proposes new potential methodological developments.

Annexes A an B include the supplementary information of the publications associated with chapters 6 and 7.

This thesis follows the bibliographic style author-year.

CHAPTER 2 STATE OF THE ART AND RESEARCH QUESTION

This chapter starts with a brief introduction to LCA and ESOMs, introducing some concepts and vocabulary that are needed to understand the thesis. Both ESOM and LCA use different terms to refer to very similar concepts, and the differences in nomenclature are needed to “navigate” the linking between both models. The first part of the chapter is largely based on two published articles (chapters 3 and 4), which document the state of the art in the modelling of the electricity sector and on the integration a particular strand of energy models with LCA. The chapter ends with the statement of the research question and the research objectives.

2.1 Basic concepts of life cycle assessment and energy system models

2.1.1 Introduction to Life cycle assessment

LCA is a widely used methodology to quantify the environmental impact of goods and services “from cradle to grave” (Hellweg and Milà i Canals 2014). LCA methods are standardised by ISO (ISO 2006a, b). LCAs are usually conducted in four steps: formulation of the goal and scope definition, a compilation of the inventory of flows, impact assessment phase and interpretation. It usually requires an iterative process, whereby the model is improved until it can respond to the goal of the assessment.

The goal and scope define the purpose of the assessment and establish details about the product system under study. Among the essential elements to define is the “functional unit”, which quantifies the functions of the system under study. In an energy system this function is quantified by several flows such as “x petajoule (PJ) of heat for residential houses” or “y million passenger-kilometers (MPkm) of road transport”. In LCA there are two broad assessment types. Attributional LCA (ALCA) analyses the impact of a given production system and consequential LCA (CLCA) studies the consequences of changes in production systems. Market forces often mediate these changes, Therefore, an analysis of market-mediated changes is required (Weidema et al. 1999; Creutzig et al. 2012). The market analysis in LCA traditionally relies on a step-wise procedure, used to systematically identify which technology will respond to a change in demand, referred in the literature as marginal technology (Weidema et al. 1999). The LCI should include all the processes that have been affected by the intervention and this has special implications for processes that produce multiple products. In the case of joint production of co-products, the displaced production by co-products is considered in the inventory, on what is known as substitution approach (Majeau-Bettez et al. 2017).

During the inventory phase the mass, energy flows and services provided by a given activity are quantified in a life cycle inventory (LCI). An activity generates products or services that can be then used by other activities. Therefore, activities can be connected to describe the production systems that fulfil the functional unit. Production systems can go from simple processes to global supply chains. This “bottom-up’ description of production systems is called process-based LCA. Products can be produced by different technologies, and often (like in this thesis) the terms activity, process and technology refer to “things that happen” (Kuczenski et al. 2016). LCA traditionally differentiate two types of flows: elementary flows and intermediate flows. "Elementary flows", are either released or extracted from the environment without previous or subsequent transformation (ISO 2006b). Elementary flows, also known as biosphere exchanges are what is broadly understood as "emissions" to the environment on ESOM (Huppmann et al. 2018). Intermediate flows are also named 'technosphere flows'. Here the terms exchange and flow are also used indistinguishably. These flows have associated metadata, notably their quality. The better the quality of an inventory is, the more reliable it is and the lower its epistemic uncertainty is. LCAs rely on databases compiling generic production systems, as building blocks of product systems, being ecoinvent (Wernet et al. 2015) the most commonly used for research purposes. Usually, the modeller adapts and creates a limited number of processes on what is known as the 'foreground', and relies on existing databases for the rest (the background) (Wernet et al. 2015). LCI only account for a limited number of flows associated to processes or product systems. For example, an insurance is required to drive a car, but burdens from operating insurance companies are rarely included in LCIs of cars. ISO recommends to define specifications of which flows will be omitted, known as "cut-off" criteria (ISO 2006b). ISO norms recommend to use mass, energy and environmental contribution as criteria (ISO 2006b), although research articles rarely specify them.

During the impact assessment phase, elementary flows are aggregated into indicators of environmental impact via the modelling of multiple cause-effect chains. These cause-effect chains are quantified in characterisation factors (CF), which enclose information about effects, exposure and fate (Hauschild and Huijbregts 2015) of substances. A well-known example of CFs are the global warming potentials of GHG, used to aggregate them into CO_{2eq} emissions. LCA distinguish between "midpoint" and "endpoint" indicators. Midpoint indicators quantify impact in an intermediary point of the impact pathway, while "endpoints" model all the way to the "areas of protection" (i.e. things we care about). Common areas of protection include human health, the natural environment and natural resources. The advantage of midpoint indicators is that they are more robust (i.e. less uncertain), the disadvantage is that they are less meaningful for decision making (Hauschild and Huijbregts 2015).

2.2.2 Introduction to energy system models

The energy system has been defined as "combined processes of acquiring and using energy in a given society" (Pfenninger et al. 2014). To understand what modellers in this domain mean by "energy commodities" it is useful to know that they were initially developed during the oil crisis (Pfenninger et al. 2014) and that the guiding principle to measure energy was the replacement of fossil fuels (Frischknecht et al. 1998). Therefore, energy system models analyse the supply and use of services supplied by fossil fuels and their potential substitutes. The demand for end-use services is the LCA equivalent to reference flows needed to fulfil the functional unit. These services may include transport, heating, but also the wide variety of services provided by electricity, depending on the scope of the assessment.

There are many varieties of energy system models, but this thesis focuses on bottom-up optimisation partial-equilibrium multisector models, the most adequate to study decarbonisation of multiple sectors (Astudillo et al. 2017a) and the backbone of energy system models (Pfenninger et al. 2014). More precisely, this thesis works with models of the TIMES framework, probably the most widely used ESOM (Pfenninger et al. 2014). The same approaches would be applicable to other similar models such as the open-source OSeMOSYS or MESSAGE.

Bottom-up models have detailed descriptions of the components of the energy system, with a technological resolution similar to process-based LCA. Processes (also referred as technologies (Huppmann et al. 2018)) produce energy commodities (technosphere flows in LCA) or emissions (biosphere flows in LCA) and the ensemble of the production system is known as reference energy system (RES). The RES is what in LCA is called "product system". Bottom-up models are also called "technology-rich models" because of the variety of technologies described in the system. Models can easily have more than 4,000 technologies defined (chapter 5). The partial-equilibrium assumption means that markets outside the system under study are assumed not to be affected by changes within the system. For example, changes in the demand for oil from Quebec are assumed not to affect global oil markets. This notion is similar to the concept of "background" and "foreground" in LCA, where the foreground is the RES under study, and the background is not affected by changes within the system.

The purpose of ESOMs is to help planning future infrastructures, using economic optimisation to identify desirable futures (hence its normative nature). Cost-optimal systems maximise the 'utility' of the system, measured as the total surplus, an indicator of total social welfare (Loulou et al. 2005; DeCarolis et al. 2017), therefore optimised solutions are considered desirable. To simplify the optimisation problem, perfect competition is a common assumption in these models. However, many models start to incorporate consumer preferences to better reflect "real-world transitions". Therefore, ESOMs are not purely normative and also aim to have some explanatory power of how the future may unfold. ESOMs can have constraints to the optimisation problem. These can be used to restrict the space of desirable futures (e.g. limiting the total greenhouse gas emissions). Constraints can represent technical impossibilities (e.g. range limitations of battery-based vehicles) and are also used to model more realistic technological uptakes.

One of the limitations of ESOMs is their oversimplified modelling of human behaviour, which is known to deviate from cost-optimisation (Tversky and Kahneman 1974; Creutzig et al. 2018). This limitation is more relevant when models are used to explain what can happen than when used for normative assessment (i.e. to determine what choices should be made). It has long been argued that, argued that normative and descriptive analysis of choice should be separated, because of the limitations of rational-choice models to represent real-world situations (Tversky and Kahneman 1986). Still, retrospective analyses of the UK electricity sector show that real-world transitions deviated from cost-optimal scenarios, but cost were still one of the key drivers of transition (Trutnevyte 2014). The real transition fell within the region of near-optimal solutions and the author conceded that "cost optimization may not be a completely inadequate proxy for the real-world transition" (Trutnevyte 2014). Yang and Heijungs have argued that when using economic models for CLCA, assumptions on rationality should be relaxed and insights from behavioural (empirical) economics should be included (2017). The field of behavioural economics has shown how that humans deviate from cost-optimisation with systematic biases such as risk aversion or poor forecasting (Dorman 2014). Some of these systemic deviations can indeed be incorporated in TIMES models, using e.g. myopic foresight or pre-defined market shares (Astudillo et al. 2018). However, there are risks when trying to model "realistic" behaviour. Modelers may add constraints or higher hurdle rates to represent realistic technological adoptions, but given the lack of empirical evidence, there is the risk of adjusting them so the model conforms to their pre-conceptions on how the future may unfold (DeCarolis et al. 2017). This is why best-practices recommend to thoughtfully document assumptions and back them with empirical evidence. In order to facilitate the normative interpretation of results, constraints should be kept to the minimum. The removal of constraints also allows conceiving "unexpected knowns" which have been overlooked in the past (Trutnevyte et al. 2016).

ESOMs provide a range of results, including future technology capacity and utilisation, marginal commodity prices or total GHG emissions. These models are now widely used in climate change mitigation plans (DeCarolis et al. 2017). Their level of complexity can vary, from models of cities to global models. Their complexity can grow further and be linked to climate models and agricultural models. These hybrid models are called Integrated assessment models (IAMs), an example being the TIMES Integrated assessment model (TIAM) (Glynn et al. 2015).

Canadian ESOMs

This research project did not intend to create a new energy model, which would be a thesis on its own, but rather use existing models. A quick overview to the existing models for Canada (Table 1 in (Layzell and Beaumier 2018)) illustrates that the North American TIMES Energy Model (NATEM) is the only bottom-up optimisation model of Canada. It is also available at the provincial level, therefore valid to study the case of Quebec. Being of the TIMES family, which is used by 77 institutions in 37 countries (Layzell and Beaumier 2018), solutions applied to NATEM can be extended to other cases. NATEM has been used to study a range of issues, from provincial to national (Vaillancourt et al. 2017, 2018, 2019).

2.2 Limitations of life cycle assessment and energy system models

LCA limitations

In the context of modelling energy systems, LCA has big limitations to model representative and complete inventories (Astudillo et al. 2017a). The step-wise procedure used in CLCA cannot grasp the complex interactions in the energy systems and LCA needs other models to foresee which technologies will be part of future energy systems and which would be their characteristics (Astudillo et al. 2017a). For example, a new heat-pump may substitute gas-fuelled boilers, but this uptake will impact prices of gas and electricity, affecting other interconnected markets. LCA also assumes linear response to changes, ignoring non-linearities considered by energy models (Yang and Heijungs 2017). Examples of non-linear response may arise from reaching constraints, such as available potential for hydropower expansion.

LCA is also ill-prepared to understand the economic implications of energy transitions, and these implications are essential for the feasibility of energy transitions. Finally, integration with ESOMs may erode model transparency, unless the model is well documented (Astudillo et al. 2017a).

Multisector ESOM limitations

The main limitation of ESOMs to analyse the impact of economic activities on humans or ecosystems is their limited modelling of cause-effect mechanisms. ESOMs only model a few emissions (Astudillo et al. 2017a, 2018; Pauliuk et al. 2017). In their most comprehensive forms, they integrate land-use modelling (e.g. (Huppmann et al. 2018)) but they lack the comprehensive impact assessment methods and inventory of LCA.

ESOMs like LCA, require data of future technologies, and although generic data from other models is often valid, parameters of some technologies need to be regionally adapted. This is notably the case for variable renewable energy (i.e. wind, solar and run-of-river), changes in the building envelope of buildings (Astudillo et al. 2017b).

Technology-rich models define the ‘function of the system’ by the definition of end-use services. End-use services (e.g. household heating), are usually subdivided into different groups with demands that evolve independently (e.g. apartments, houses). This division of demand is crucial because it determines the substitutability of services. Division of energy services (e.g. transport by large cars, SUVs or buses) is meant to model the heterogeneous consumer preferences (DeCarolis et al. 2017). However, it rules-out potential mitigation opportunities, such as increased use of public transport or switching housing types, which may be very effective. This feature has been described as “reductionist fallacy” where it assumed that components of the energy demand would remain the same in the foreseeable future (Wene 1996).

TIMES - LCA studies

Bottom-up multisector ESOMs like those of the TIMES family have clear advantages to study a case like Quebec, where most of the GHG emissions occur outside the electricity sector but require electricity to reduce emissions (Astudillo et al. 2017a). They have also a similar level of “resolution” minimising information loss between models.

The integration of TIMES and LCA models pass by exchanging information at process/technology level. There is a growing number of studies linking TIMES and LCA, reviewed in Astudillo et al. (2018) (chapter 4). Since its publication, some other related publications emerged, notably (Arvesen et al. 2018; Mendoza Beltran et al. 2018; Volkart et al. 2018). The remaining methodological challenges can be summarised as follows:

Completeness (Mapping processes between both models): large TIMES models often have several thousands of technologies defined and are continuously updated. Finding and adapting an equivalent to those technologies to LCA counterparts is unfeasible. Even if not all are involved in a given scenario, when analysing changes in the system, often several hundreds of processes are affected by interventions (Astudillo et al. 2018), which is a similarly daunting task. To date, the only existing CLCA assessment has been done on a model with a reduced number of technologies (Astudillo et al. 2018, 2019). Astudillo et al. (2018) proposed the use of a cut-off rule to address the mapping problem, using the GHG accounting of the TIMES model as cut-off criteria.

Representativeness: LCA databases such as ecoinvent represent existing production systems, but databases would need to be adapted to represent future ones, coherent with ESOMs modelling. The adaptation involves harmonising parameters such as efficiency, or changes in fuel mixes. Just very recently, Mendoza-Beltran et al. (2018) have started to tackle a systematic adaptation of efficiencies using data from IAMs. However, the procedure is meant to adapt the background of the system, not the foreground, which is the part affected by the energy policy. In TIMES models the same process can have different efficiencies over time. Therefore the average efficiency in a time period depends on when the investment takes place and is scenario specific. These procedures would need to adapt fuel consumption as well as emissions to model the effect of fuel changes.

Double counting: we identified double counting as a problem in previous studies (Astudillo et al. 2018). Double counting will occur if ESOMs and LCA are ‘connected’ carelessly at different parts of the supply chain. For example, an energy system could have electricity production process and a plug-in car consuming part of this electricity. If the production volumes of both processes are included in the demand, burdens from electricity use by the plug-in car would be double counted. Volkart et al. proposed a viable approach and applied to a MARKAL model very recently (2018). The idea is to set to zero the technosphere flows associated with energy commodities present in the TIMES model. This approach is viable but challenging to implement together with a cut-off approach proposed in Astudillo et al. (2018) and implemented in Astudillo et al. (submitted) (Chapter 6).

Another type of double counting occurs when TIMES models include as final demands what are intermediate products in LCA product systems. For example, heavy freight transport is a final demand in NATEM but other final demands require heavy freight transport as intermediate services. These dependencies are not modelled in TIMES models, and but are included in LCA product systems. This can result in double-counting and inaccuracies in the modelling (Astudillo et al. 2018). Ideally, changes in final demands (e.g. electrification of road freight or changes in the production of clinker) should be taken into account in LCI of processes in the region under study. Moreover, the total demand from LCA production systems should be discounted from the demands as defined by the TIMES model. However, it is unclear if these increases in accuracy are worth the effort, and procedures to quantify the impact of these ‘feedback’ effects are needed.

Transparency and reproducibility: except for some studies (Rauner and Budzinski 2017; Mendoza Beltran et al. 2018) the inner workings of integration efforts have not been made public. A workshop of LCA researchers working on this domain found that there is a lot of overlap and wasted efforts because of, among other things, lack of transparency on the data manipulation steps (Vandepaer and Gibon 2018). The use of open-source software and common procedures were seen as step-forward to avoid waste of resources (Vandepaer and Gibon 2018). Reusability can indeed improve the impact of research, while transparency is vital to the credibility of the results, inside and outside academia.

2.3 Common vocabulary between models

To link models there should be areas of overlap where both models have representations of the same reality (Wene 1996). Models should have a common specification of concepts, terms and definitions to communicate effectively, also referred as ontology (Pauliuk et al. 2016). Therefore, an initial step is to identify these areas of overlap.

TIMES commodities have several numeric and non-numeric characteristics that are common with LCA exchanges that can be used in the integration process. TIMES has a wider range of exchange typologies: energy, material, demand service, emissions and financial. The distinctions are enough to differentiate technosphere (energy, material and demand services) from biosphere flows (emissions). It also allows to identify the reference flows (ISO 2006b) from other technosphere -intermediate- flows. TIMES commodities, as LCA exchanges have units, which need to balance equations.

TIMES processes also have characteristics similar to those of LCA processes. While LCA processes are typically divided into market processes or transforming activities, TIMES processes have a wider typology range. Of particular use is the differentiation of importing and exporting processes, and processes delivering final demands (Gargiulo et al. 2016). Both exports and -internal- demand represent the overall demand for energy services of the model. TIMES processes can have efficiencies, which can be a function of inputs (e.g. a gas power plant being less efficient when using oil) or outputs (e.g. heat pumps being more efficient to deliver heat than refrigeration). Efficiencies can also change with time to represent technological progress, this means the same process can have different efficiencies in different scenarios, depending on when investment takes place. Unlike LCA, processes and generated commodities can have different units. For instance, a car may have *Vehicle km* as activity units and deliver the commodity in *persons km*. This requires an extra attribute (ACTFLO) (Gargiulo et al. 2016) which in this case represents the average occupancy (persons per vehicle). This attribute is also useful as sometimes LCA processes are defined in *person km*, vehicle km or tone km.

Emissions can be either associated with the consumption of a commodity (e.g. CO_2 emissions per tonne of coal burned) or the output of an activity (CO_2/kWh electricity). NATEM opts for defining emissions factors as a function of fuel input, the same procedure used in national inventories of GHG emissions (Environment Canada 2017). Therefore, emissions per unit of activity depend on the efficiency, activity levels, and the type of fuel consumed.

Table 2.1: Vocabulary differences between LCA and ESOMs

LCA term	ESOM term
Activity / process	Process / technology
Biosphere exchange / elementary flow	Emission
Technosphere exchange/ intermediate flow	Energy commodity
Reference flows	End-uses
Background	What is outside the partial-equilibrium model
foreground	What is inside the partial-equilibrium model
Product system	Reference energy system

2.4 Research question and objectives

The decarbonisation of energy services is increasingly pressing, and integrated approaches are needed to avoid unintended harmful consequences. These potential consequences can be foreseen through the integration of LCA and ESOMs (Astudillo et al. 2017a, 2018).

This thesis intends to elicit which are the cost-optimal technological options to reduce GHG emissions from the energy system in Quebec, and if the introduction of these technologies will "backfire" (i.e. result in additional impacts unforeseen by ESOMs) when analysed from a life cycle perspective. Additionally, an objective is to know the nature and amount of the transition economic costs. These questions are a specific formulation of the more generic question "how to softlink large bottom-up ESOMs and LCA to analyse the potential consequences of energy transitions?". *Large* refers to models with several thousands of technologies defined.

Answering this question can be subdivided in the following intermediate objectives:

1. Revise the state of the art on the linking of ESOMs and LCA
2. Adapt NATEM-Quebec to address specific policy questions related to the household and transport sector:
    - Which heating systems should be used to reduce societal costs?
    - Would better-insulated buildings be a cost-effective mitigation option?
    - How different urban planning would affect transition costs?
    - If the GHG from reservoir impoundment are considered in NATEM, would it affect the solution?
    - How does the generation of variable renewable energy (wind, solar and run-of-river) and imports match the electricity demand, concentrated in winter?
    - Which powertrains are the cheapest options to reduce emissions in the long-term?
    - Which are the cost-optimal ways to produce electricity when emissions from reservoirs and temporal distribution of variable renewable energy are considered?
    - How much the energy transition could cost and what is the nature of these costs?
3. Link NATEM and LCA databases to conduct CLCA, addressing the gaps in the literature, namely
    - Overcome the complexity of mapping two large bottom-up models.
    - Adapt LCI to represent future supply chains and be coherent with NATEM.

- Create an LCI that can be subject to contribution analyses. This implies not doing corrections at ‘indicator level’ but instead build a coherent LCI.

- Validate combustion emission factors

2.5 Original contributions

- Identification of methodological needs on the integration of ESOMs and LCA

- Improvement of NATEM-Quebec to analyse specific policy questions.

    - Link NATEM-Quebec with building simulation to evaluate new thermal envelopes.

    - Time series analysis to characterise variable renewable energy (wind, solar and run-of-river), the temporal distribution of heat demand and temporal availability of imports.

    - Update transport (road passenger, road freight and air) and heating technologies to model future technologies adapted to the regional context.

- Develop a reproducible method to integrate technology-rich ESOMs and LCA

    - Develop an approach to simplify the mapping between ESOMs and LCA.

    - Develop methods to adapt inventories of existing technologies to represent future ones.

    - Evaluate the impacts on biodiversity and human health of a global warming mitigation strategy allowing for contribution analyses.

    - Develop methods to quantify ‘feedback effects’ (i.e. the effects of changes in what TIMES models consider final demands and LCA intermediate services) and potential ‘double counting’.

    - Compare combustion emission factors.

- Evaluate the potential costs of a GW mitigation policy in Quebec and the main factors associated with these costs.

CHAPTER 3 CHALLENGES AND OPPORTUNITIES TO IMPROVE DATA QUALITY OF ELECTRICITY PRODUCTION MODELS. A LITERATURE REVIEW.

Avant-propos

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Titre en français: Inventaires du cycle de vie de la production électrique suivant une perspective de qualité des données.

Contribution au document : revue de littérature sur la modélisation de la production d'électricité en analyse du cycle de vie.

Résumé :

Objet : La génération d'électricité est l'un des principaux contributeurs à l'impact environnemental global et son rôle en tant que vecteur d'énergie devrait se développer considérablement. Par conséquent, des inventaires fiables et précis des flux de matières et d'énergie associés à la fourniture d'électricité sont essentiels dans les évaluations environnementales. Cet article a pour objectif de résumer les défis et les opportunités existants dans la modélisation des inventaires de cycle de vie (ICV) de l'approvisionnement en électricité, du point de vue de la qualité des données.

Méthode: Nous passons systématiquement en revue l'état de l'art en matière ICV de l'approvisionnement en électricité actuel et futur. L'analyse est structurée en fonction des

caractéristiques de qualité des données proposées dans l'ISO 14044: 2006: représentativité, exhaustivité, cohérence, reproductibilité, incertitude, sources de données et précision.

Résultats et discussion: En examinant les ICV existants du point de vue de la qualité des données, nous constatons des difficultés pour obtenir des données représentatives sur le plan temporel et technologique, tandis que des données représentatives sur le plan géographique ne sont toujours pas disponibles pour certaines régions. De plus, les méta-analyses ont rencontré des problèmes de reproductibilité, qui, combinés à un manque de cohérence entre les études, gênent la comparabilité entre les études. De plus, certains flux tels que les émissions fugitives ont été sous-estimés. Les problèmes mentionnés ont un impact négatif sur la qualité des ICVs. Nous fournissons ici des recommandations sur la manière dont plusieurs méthodes telles que les modèles d'équilibre, la régression ou le paramétrage peuvent être utilisées pour améliorer la qualité des données, étayées par des formats de données plus puissants. Des modèles open-source, des plateformes de données ainsi qu'une liste des paramètres clés à déclarer sont suggérés pour faciliter la reproductibilité et améliorer la transparence de l'ICV.

Conclusion: Plusieurs méthodes et ressources peuvent être utilisées pour améliorer l'ICV de l'approvisionnement en électricité, permettant ainsi des analyses plus ambitieuses et plus puissantes. Néanmoins, il convient de faire attention aux compromis entre différents aspects de la qualité des données. Par exemple, des modèles plus complexes et précis peuvent entraîner une perte de transparence et de reproductibilité, à moins que des efforts supplémentaires de documentation ne soient déployés. D'autres approches, telles que la paramétrisation systématique, ne compromettent pas la qualité des données et devraient être utilisées pour améliorer la cohérence et la reproductibilité des inventaires.

Abstract

Purpose: Electricity is one of the main contributors to global environmental impacts, and its role as an energy carrier is expected to grow substantially. Consequently, reliable and accurate inventories of material and energy flows associated with electricity supply are essential in environmental assessments. This article aims to summarize existing challenges and opportunities in the modeling of life cycle inventories (LCI) of electricity supply from a data quality perspective.

Method: We systematically review the state-of-the-art in LCI modelling of current and future electricity supply worldwide. The analysis is structured according to the data quality characteristics proposed in ISO 14044:2006: representativeness, completeness, consistency, reproducibility, uncertainty, data sources and precision.

Results and discussion: Looking at existing LCI through the lens of data quality, we observe difficulties in obtaining temporally and technologically representative data, while geographically representative data is still unavailable for some regions. Moreover, meta-analyses encountered issues of reproducibility combined with a lack of consistency across studies, impeding inter-study comparability. Additionally, some flows such as upstream fugitive emissions have been underestimated. The aforementioned issues have a negative impact on the quality of LCI. Here we provide recommendations on how several methods such as equilibrium models, regression or parameterization can be used to improve data quality, underpinned by more powerful data formats. Open-source models, data platforms as well as a list of key parameters to be reported are suggested to facilitate reproducibility and enhance transparency of electricity LCI.

Conclusion: There are several methods and resources that can be used to improve LCI of electricity supply, enabling more ambitious and powerful analyses. Nonetheless, special care should be taken concerning tradeoffs between different data quality aspects. For instance, more complex and accurate models may result in a loss of transparency and reproducibility unless additional reporting efforts are conducted. Other approaches, such as systematic parameterization do not compromise data quality and should be used to improve the consistency and reproducibility of inventories.

Keywords: electricity, LCI, consumption mix, data quality, representative, uncertainty

3.1 Introduction

Electricity supply is often highlighted as a significant hot spot in LCA results for a majority of product and service life cycles (e.g. (Curran et al. 2005; Treyer and Bauer 2013)). It is one of the main sources of environmental burden in several sectors such as buildings or information and communication technology (IEA 2013a; Arushanyan et al. 2014). Electricity supply was also the largest emitting sector, with around 38% of direct world CO_2 emissions in 2013 (IEA 2015).

Several facts illustrate the growing importance of the electricity sector in the global economy. Since 1970, the electricity share of overall energy demand has risen from 9% to 17% (IEA 2014a). The trend is likely to accelerate because most of the climate change mitigation scenarios pass by a gradual electrification of energy supply, substituting fossil fuels in services such as transport and household heating (Williams et al. 2012; IEA 2014a). The International Energy Agency (IEA 2014a) predicts a rise between 80% and 130% of current production levels by 2050 in its climate change mitigation scenarios. Global electricity production is also expected to change radically to meet climate mitigation targets, with increasing penetration of intermittent renewable energy systems and increased use of novel technologies such as carbon capture and storage and smart grids (IEA 2014a).

In life cycle assessment (LCA), inventorying material and energy flows is one of the most critical and time-consuming phases of the analysis. Back in 2001 a special workshop on life cycle inventories (LCI) of electricity production covered many of the challenges faced in LCI of electricity (Curran et al. 2005). The topical areas identified in advance and discussed included marginal vs. average mixes, co-product allocation, system boundaries, current and future technologies. The LCI of electricity has improved since, but several issues are still prevalent. In addition, various guidelines on how to build generic LCI datasets have been set up and published (ISO 2006b; UNEP 2011), which should be considered today.

This review aims to provide an updated vision of electricity LCI from a data quality perspective, covering inventories along the supply chain of the technologies and at the electricity mix level. Developing inventories of sufficient quality to meet the increasingly complex LCA scopes is a challenging task. We summarize and discuss these challenges and propose approaches to overcome them. Potential applications of the review include critical assessments of the quality of electricity LCI (section 3.2) and the identification of methodological approaches with potential to improve data quality (section 3.3). The analysis is valid for both attributional and consequential perspectives, although we expect it to be more useful for the latter, as consequential LCI are comparatively underdeveloped. The review builds on a book chapter with the focus on life cycle management (Astudillo et al. 2015b), which has been adapted and substantially extended.

3.2 Data quality issues of LCI of electricity supply

This section covers the identified methodological challenges and data gaps faced in LCA of electricity, exclusively looking at the life cycle inventory (LCI) phase. The review is structured according to the data quality requirements proposed in ISO 14044:2006 (2006b), that is: representativeness (geographical, temporal and technology coverage), completeness, consistency, reproducibility, precision, uncertainty, and data sources. Challenges are summarized in Table 3.1 and discussed in the following subsections.

Table 3.1 Methodological challenges in LCI of electricity supply categorized by data quality indicator.

Quality indicator	Challenge
Geographical coverage	- ‘Un-traceability” of electricity and congestion challenge the selection of geographical boundaries of electricity markets and mixes. - Data gaps in non-OECD countries: inventories are inexistent or subject to high uncertainty.

	- Grid congestion affects the abatement of emissions but it is often ignored.
Temporal representativeness	- Electricity mixes representative of peak or very long (e.g. decadal) periods are often not available but are relevant for certain systems. - Delay in availability of consistent statistical information often leads to partially outdated market data. - Long-term future and marginal electricity mixes are substantially uncertain and depend on many factors. - Short-term dynamics are critical in electricity markets but often neglected in LCA.
Technology coverage	- Existing inventories and studies do not sufficiently cover the diversity of technologies under operation. - High uncertainty over emission factors of certain technologies. - Lack of data for technologies with minor installed capacities and/or potentially important technologies in future. - High uncertainty concerning characteristics of future technologies
Completeness	- Material flows that are difficult to measure are often omitted. The use of proxies improves completeness at the expense of representativeness.
Consistency and reproducibility	- Studies are often unreproducible due to poor documentation hampering the efforts to generalize conclusions.
Precision and uncertainty	- Poor temporal, technological, or geographical representativeness increases uncertainty, reducing usability of datasets.

3.2.1 Geographical coverage

The geographical coverage is the geographical area from which data for unit processes should be collected to satisfy the goal of the LCA study. In section *underrepresented geographical areas* we review differences in LCI availability by region and in section *delimitation of electricity mix boundaries* how the un-traceability affects the delimitation of geographic system boundaries.

Underrepresented geographical areas

Historically, LCI have focused on Europe and US, but with the rise of global supply chains and outsourcing of manufacturing, the need to increase the geographical scope becomes apparent. Recently, the geographical scope of inventory data has increased significantly. The database ecoinvent version 3.2 covers 89% of global electricity production in 2012 (Ecoinvent 2015), with country or region-specific LCI data showing substantial differences between specific countries and regions. Despite the geographical coverage increase, gaps in LCI keep existing and are in general more pronounced in non-OECD countries, where often extrapolations and use of proxy values are unavoidable (Treyer and Bauer 2013), increasing epistemic uncertainty.

One of the notable data gaps in LCI is the African continent (Curran 2006; Treyer and Bauer 2013), particularly with respect to market shares of employed technologies. While Africa represents a small proportion of total generation capacity, its production capacity is expected to quadruple from 2014 to 2040 (IEA 2014b). Africa is also the continent that drives global population growth and with the acutest need of access to electricity.

Delimitation of electricity mix boundaries

Electricity is untraceable once it is in the transmission and distribution system (Weber et al. 2010; Itten et al. 2014). Therefore, it is not possible to exactly know which power plants have produced the electricity supplied to consumers. To overcome this problem the common approach is to define an electricity mix within a certain geographical boundary, which represents the average electricity supplied to the consumers of a specific region (the consumption mix) (UNEP 2011). Consumption mixes account for electricity production within the region and electricity trade with adjacent regions (UNEP 2011). Usually, national boundaries are selected as boundary delimitations of consumption mixes, the underlying justification is that neighboring countries have either physical or administrative constraints to trade (Treyer and Bauer 2014). Nonetheless, regionalized inventories, overlapping with national boundaries are also available, raising the issue of what level of spatial aggregation should be used. Different levels of aggregation will result in "winners and losers" (Weber et al. 2010), including suppliers of electricity but also consumers as both can be affected by environmental policies. To explore the resulting equity issues regionalized inventory data is needed, but its availability is often limited.

Moreover, consumption mixes can be calculated in different ways depending on the consideration of electricity imports and exports (Itten et al. 2014). Ideally, consumption mixes would be based on electricity declarations from all utilities in a country. In the many cases where this information is not available, consumption mixes can be calculated as the domestic production plus imports, with the import-mix defined as the consumption mix of the exporting region. The latter approach is the one used in ecoinvent for most countries (Treyer and Bauer 2014).

Additionally, the congestion of transmission and distribution lines limits electricity supply, and has been shown to affect LCI results considerably. A recent study of wind power generation in Ontario (Canada), showed how abatement of greenhouse gases (GHG) in congested hours was about 30% lower than during uncongested hours (Amor et al. 2014a). Even if these empirical estimates cannot be generalized to other contexts, the study underscored the importance of congestion in defining the electricity mix boundary. In effect, a look at how European electricity trade is affected by congestion show how uncongested areas do not necessarily coincide with national boundaries (Breuer et al. 2013).

3.2.2 Time-related coverage

The consumption mixes change constantly over time. For simplicity, annually averaged electricity consumption mixes are often used. However, there is compelling evidence that intra-annual and inter-annual changes in electricity mixes can substantially affect LCA results, potentially biasing the LCA interpretations. Rinne and Syri (2013) studied electricity consumption mixes in Finland, finding higher emissions per unit of electricity during winter. In such a case, a yearly-averaged consumption mix biased comparisons between electric and fossil fuel heating systems. Another case study in the US accounted for inter-annual changes in emissions, resulting in reductions above 50% in several impact categories with respect to the static inventory (Collinge et al. 2013). Indeed, inter-annual changes on environmental burden per kWh of electricity are rather common, as a study including 199 countries demonstrated (Laurent and Espinosa 2015). As a result, the longer the product lasts, the more likely that inter-annual changes in the electricity mix affect LCA results. In sum, evidence calls for a more detailed analysis of short and long-term dynamics of electricity supply, particularly for the assessment of processes consuming or producing electricity during peak times or very long periods.

Obtaining past yearly-averaged country production mixes is relatively straightforward using national statistics. Typically organizations such as IEA provide compilations of national statistics, even if the often-rough categorization of fuel and power plant categories in the statistics calls for assumptions and extrapolations increasing uncertainty associated with data quality. Determining the consumption mixes – which do account not only for the domestic production but also for imports and exports – is more challenging. Detailed data on the origin or addressee of imported/exported electricity as well as details on involved power sources are usually not available. In general, the drawback of using consistent statistics applied to several countries or regions is that these statistics are always published with a delay of one or two years. Together with data handling, this leads to delays in the publication of electricity mix LCI data. Data age is even more problematic when input-output data is used to develop LCI, as data is usually several years old (UNEP 2011). The delay constitutes an example of the tradeoff between consistency and temporal representativeness. In the following section, the considerably more challenging problem of accounting for temporal dynamics in the study of changes in electricity supply is discussed.

Long term

In the long-term, new infrastructure will need to be installed to cover prospected changes in demand and substitute ageing plants. Long-term changes in electricity mixes depend on political, environmental and economic considerations that are substantially uncertain and country specific and change over time. This section reviews different approaches used to estimate prospective electricity mixes, which can be used in both CLCA or ALCA. In prospective ALCA an average of the future electricity mix would be used, while in CLCA processes are only included to the extent of their expected change (Zamagni et al. 2012).

CLCA often follows the step-wise procedure (Ekvall and Weidema 2004; Weidema et al. 2009) to identify technologies affected by changes in supply or demand. Ekvall and Weidema (2004) acknowledged that any change can be expected to result in long-term and short-term effects, affecting investments in various technologies but for simplicity, the step-wise procedure focuses on long-term marginal changes, which will typically identify a single marginal technology. For the case of markets with limited storage capacity (such as electricity supply), temporal segmentation has been suggested (Ekvall and Weidema 2004); however, there is a dearth of examples of how temporal segmentation would be done in practice. Yet, changes in the electricity sector are likely to affect a range of technologies (Pehnt et al. 2008; Mathiesen et al. 2009) and it is not a straightforward task to consistently identify these various marginal technologies with a heuristic approach (Zamagni et al. 2012; Earles et al. 2013; Menten et al. 2015). Mathiesen et al. (2009) discussed difficulties in the definition and identification of marginal technologies in a review of marginal electricity mixes in CLCA studies. They found that various techniques for determining the marginal mixes have been applied, with various scopes and time resolutions. While some of them are built following the step-wise procedure set up by Weidema et al. 2009, others lack detailed explanation on the choice of the marginal technologies or use the procedure inconsistently. In general, they concluded that the identification of marginal technologies is important but difficult and resulting marginal electricity mixes are rather arbitrary. Frischknecht and Stucki (2010) pointed out that a marginal mix needs to include information on "market reactions, production volume developments, technology developments, capacity constraints etc." In sum, an accurate and consistent identification of marginal technologies requires a deep knowledge of the local markets and it is questionable that practitioners can factor all aspects without the aid of formal mathematical modelling.

To overcome these limitations, energy system models are increasingly used in combination with LCA. These models include the electricity sector within a larger energy system, encompassing also other sectors such as heating and road transport (Figure 1), which are expected to become one of the drivers of electricity demand (IEA 2014a)(IEA, 2014a). Some examples are the World Energy Model developed by IEA (e.g. (Hertwich et al. 2015)), MESSAGE, created by the International Atomic Energy Agency (e.g. (Portugal-Pereira et al. 2016)), models from the TIMES family (e.g. (Menten et al. 2015)) or general and partial equilibrium models (Dandres et al. 2011; Igos et al. 2015). These models generate future scenarios under a series of assumptions such as cost optimization and perfect competition. The forecasts of IEA at national scale are just available for some countries and if researchers want to test a particular set of assumptions, alternative models need to be used. General equilibrium models aim to model the entire economy, while partial equilibrium models such as those based on TIMES focus on the energy sector with a high technological resolution, reason why they are more commonly used to predict structural changes in the energy sector. For example Menten et al. (2015) used a TIMES model to predict changes in electricity, transport and heat provision due to the hypothetic expansion of synthetic diesel. The use of energy system models allows to do a systematic identification of substitution effects, but models tend to be highly sensitive to the policy and economic context (Menten et al. 2015). Energy system models often cover wide regional and temporal scopes and to be computationally tractable use a relatively coarse temporal resolution. However, a coarse temporal resolution has resulted in an underestimation of the need of peak power plants (Kannan and Turton 2013; Deane et al. 2014) and needs special care in electricity studies.

Short-term

Several critical issues relevant in the context of power supply such as peak load coverage, transmission constraints or blackouts occur within minutes to hours and are of uttermost importance in power planning. In the short-term, production capacity is fixed and supply and demand are matched with either changes in the operation of existing power plants or demand side measures. Short-term dynamics of electricity supply are considerably complex when looked in detail, as they are conditioned by several technological, economic and policy factors, such as ramp-rate limitations, renewable incentives and fuel costs. Moreover, short-term dynamics are of growing relevance given the increasing levels of intermittent renewable energy, whose production depends on local weather conditions, intrinsically difficult to predict. The few cases where LCA studies addressed short-term dynamics were integrating LCA with models of the electricity market, also called power system models (Pfenninger et al. 2014). For example, Pehnt et al. (2008) used a stochastic (i.e. non-deterministic) model of the electricity market to analyze the substitution effects of increasing levels of offshore wind energy in Germany.

An alternative approach to study short-term dynamics is to model "what if" retrospective scenarios. For instance, Amor et al. (2014b) reconstructed supply and demand curves using market data. With the aid of a partial equilibrium model, the study identified which would have been the affected technologies if changes in demand or supply had taken place. Recent retrospective analyses also include some of the operating constraints, such as outages and spinning reserves, resulting in a significant increase in marginal emission factors (Raichur et al. 2015).

3.2.3 Technology coverage

Electricity supply is technologically very diverse, with a wide range of technologies at different levels of development, often operating simultaneously. Moreover, future energy mixes will include technologies that are currently under development and whose life cycle inventories and thus environmental consequences are yet unknown. This diversity complicates the development of representative datasets of electricity supply. This section covers the areas for which we see the most urgent need for improving data quality, for both current and future technologies.

Current technologies

There is a wide variation among generation plants in terms of operational emissions and inputs per unit generation, across and even within fuel and technology types. As a result, literature estimates of environmental burdens for the same technology can vary a lot (e.g. (Warner and Heath 2012; Whitaker et al. 2012; Burkhardt et al. 2012; Hertwich 2013; O'Donoughue et al. 2014). For example, existing literature estimates of GHG emissions from coal power plants range from 675 to 1689 g CO_{2eq}/kWh (Whitaker et al. 2012), largely attributable to differences in power plants characteristics such as the type of combustion unit. Despite the large differences between technologies, often, different power plant technologies within one type of primary energy carrier are aggregated due to lack of technology-specific data such as efficiencies, emissions, and annual production volumes (Treyer and Bauer 2013). For example, coal power plants today can be operating in subcritical, supercritical, ultra-supercritical or circulating fluidized bed mode or can use pulverized coal or gasified coal in integrated gasification combined cycle plants. Such variations are often not reflected in inventories, but LCI data of one fuel-specific generation technology (e.g., hard coal power plant) represents a generic mix of different power plant technologies and operation modes. However, the generic fuel type "coal" (as often reported in statistics) can (and should) be split into more specific types such as "hard coal" and "lignite", in order to properly reflect fuel-specific characteristics in LCI data such as emission parameters and ash content.

Specification of the time frame of "current" LCI data can also be challenging: statistical sources often refer to different years and up-to-date data is not always available. In addition to that, there is considerable uncertainty over certain emission factors, even for mature technologies such as hydropower. This uncertainty often stems from our poor understanding of natural processes. If we take the example of hydropower, there is a strong spatial and temporal variability of methane emissions from reservoirs, and the origin of this variability is not yet well understood (Hertwich 2013). Furthermore, possible changes in downstream emissions have not been quantified yet (Teodoru et al. 2012). Finally, some technologies with currently minor installed capacities such as geothermal, solar thermal, wave and ocean power, and certain wind and photovoltaic technologies are not (yet) included in background databases (Treyer and Bauer 2013). Without representative LCI, it is not possible to evaluate whether these technologies constitute an environmentally desirable alternative.

Prospective technologies

Innovation and technological development are key factors in the global environmental impact of societies. There is indeed a lot of hope in the role that technology can play in sustainable energy futures (Arvesen et al. 2011; IEA 2014a). During the research and development (R&D) of new technologies investors often require a forecast of future performance since they need to reduce uncertainties concerning the expected returns. LCA is increasingly used in R&D and has proved to be essential to identify potential environmental issues at an early stage. Different methods have been used to extrapolate environmental performance such as field experiments (Espinosa et al. 2014), regression analysis (Caduff et al. 2012) or expert consultation (Heck et al. 2009). For example, the LCA of organic photovoltaics identified potential toxicity issues but also encouraging improvements in cumulative energy demand (Lizin et al. 2013). Volkart et al. (2013) provided estimates of potential GHG emission reduction due to carbon capture and storage in future fossil power generation and cement production using data from pilot plants and learning rates based on historical developments and estimated trends for e.g. power plant efficiencies and emissions. This was coupled with partially adapted background LCI data reflecting expected technology development in other economic sectors. New technologies impose additional difficulties on the modeler as they often make use of new materials and manufacturing processes that do not yet exist in LCA databases.

Technological development can be integrated in technology explicit models such as those based on TIMES paradigms, defining learning rates (i.e. changes in costs and efficiencies over time). Learning rates can be modelled as exogenous to the model or be affected by internal variables, like cumulative installed capacity (endogenous learning or learning-by-doing). Nonetheless, it has been found that endogenous learning can lead to unrealistic investment decisions, which often need to be manually adjusted (Loulou et al. 2005), questioning their utility. This issue is particularly problematic in models that assume perfect foresight.

Very few databases allow studying the potential life cycle impact of technological development. This gap was explicitly addressed in the NEEDS database, which provides to date the only existing open integrated LCI on future electricity production technologies (NEEDS 2009). The NEEDS project modelled material requirements and emissions of future technologies based on current inventories and expert judgement consultation. The predicted costs together with forecasts on energy demand were used in a TIMES model to model future consumption mixes. Nevertheless, results should be interpreted with caution. While it is expected that efficiency and costs improve over time, it is very difficult if not impossible to foresee which materials or techniques will be used to attain these improvements. The uncertainty of LCI would be even larger if disruptive and breakthrough innovations are considered, as they can transform electricity markets in unexpected ways. Examples of potentially disruptive technologies in the energy sector include smart meters or grid scale storage, which can have a large impact on electricity consumption mixes.

3.2.4 Completeness

Completeness refers to the percentage of flows that are covered (ISO 2006b). A complete inventory of all the flows is rather unattainable, and inventories are always to some extent incomplete. Flows that are difficult to measure (such as electricity theft or gas leakage) are particularly susceptible to be unintentionally omitted. Process-based inventories are more prone to truncation errors and generally result in an underestimation of environmental impact compared with those derived from input-output inventories. Furthermore, there is a number of flows such as nanomaterials, or noise that are not yet inventoried, despite being relevant for certain technologies. Finally, in the absence of better data proxies from other processes are often used, improving completeness at the expense of poorer representativeness. Readers should note that this approach is considered as a last resort according to UNEP guidelines and should be justified on individual basis (UNEP, 2011).

3.2.5 Consistency and reproducibility

Meta-analyses of LCI of electricity production have found a lack of consistency across studies (Heath and Mann 2012). The lack of consistency across studies, while often legitimate, hampers inter-study comparability and the analysis of the extent and origin of variability. Part of these inconsistencies can be addressed harmonizing assumptions across studies (e.g. using the same system boundaries), as the National Renewable Energy Laboratory (NREL) did in a series of meta-analyses of electricity production technologies (Heath and Mann 2012; Hsu et al. 2012; Padey et al. 2012; Warner and Heath 2012; Whitaker et al. 2012; Burkhardt et al. 2012; O'Donoughue et al. 2014; Heath et al. 2014) Nonetheless, the NREL harmonization effort was hampered by a lack of transparency in the studies (Price and Kendall 2012) which questions whether reproducibility is actually feasible. Indeed, critical surveys often have to exclude plenty of studies due to poor documentation (Sovacool 2008). With respect to CLCA, reviews found clear inconsistencies and lack of documentation with respect to the identification of marginal technologies (Mathiesen et al. 2009; Zamagni et al. 2012). Therefore, the combination of inconsistent methods across studies, together with poor documentation, limits the research impact of the growing literature on LCI of electricity.

Claims on the need of transparency in LCI are not new (Frischknecht 2004). Despite the ISO standard is unequivocal in respect to the reporting requirements (e.g. quantitative data quality assessments, description of each unit process, all calculation techniques and reference all data from public sources shall be included), reproducibility issues seem to still be prevalent. Lack of transparency and reproducibility is also a common criticism of energy system models (Pfenninger et al. 2014) which are increasingly used in LCA. Unless reporting is improved, the integration with energy system models will improve representativeness at the expense of a loss of reproducibility.

3.2.6 Precision, uncertainty and data sources

Precision refers to the variability on the magnitudes to be measured (ISO, 2006). As previously mentioned, there is considerable inherent uncertainty over certain emission factors, even for mature technologies. This issue is more prominent in emissions that are more difficult to measure or to predict, such as methane emissions from reservoirs (Hertwich 2013) or fugitive emissions (Kintisch 2014; Bouman et al. 2015).

The pedigree matrix procedure allows to quantify the impact of data quality on uncertainty (Weidema et al. 2013). The systematic quantification of uncertainty helps to improve data quality, although it has been noted that the selection of the scores are subject to interpretation (Ciroth et al. 2013). Furthermore, a study of Chinese coal production found that generic uncertainty factors were overused and primary data often did not fit in existing probability distributions (Henriksson et al. 2014). It is worth noting that spread in the emissions can be caused by variability and uncertainty and strategies to reduce each differ (Steinmann et al. 2014a). Despite the methodological advances, uncertainty and sensitivity analyses are relatively uncommon.

Finally, the reliability of the data sources should be taken into consideration. A comparative study of official Chinese statistics found enormous unjustified differences in CO_2 emissions depending on whether aggregated provincial statistics or national were used (Guan et al. 2012), largely due to differences in coal production statistics. The example illustrates the importance of cross-checking the validity of the data used, particularly in cases where the monitoring process is opaque or controlled by politically dependent agencies (Guan et al. 2012).

3.3 Key research opportunities

This section evaluates the opportunities to improve the quality of LCI of electricity supply. The approaches are especially relevant for but not limited to studies in which electricity is in the foreground of the system under study. Section 3.3.1 addresses temporal issues, section 3.3.2 describes methods to address technology data gaps. Finally, section 3.3.3 introduces some of the key opportunities underpinned by structural changes in data formats. A summary of opportunities is available in Table 3.2.

Table 3.2: Summary of research opportunities in LCI of electricity supply, including potential uses and concerned quality indicators

Research opportunity	Possible uses
Integration with economic models in prospective and retrospective studies	- CGE: long-term multi sector analysis, energy policies, test the validity of partial-equilibrium conditions. - Energy system models: study substitution within energy sector; identification of marginal technologies. - Short-term dispatch models: short-term substitution within electricity producers.

	- Game-theory and agent based models: analysis of strategic behavior
Hybrid LCA	- Detect truncation errors in LCI
Statistical inference models and feasibility software	- Estimate emissions and efficiency of generation units in the absence of better data. - Locate marginal generation units. - Validate data of doubtful quality.
Learning curves	- Forecast technological changes in prospective studies
Use of open-data and open-source models	- Facilitate the share of first-hand information, improving transparency and reproducibility.
New probability distributions	- Better characterization of unrepresentativeness.
Systematic parameterization	- Increase transparency and facilitate meta-analyses. Ease comparison and adaptation from generic to specific datasets.

3.3.1 Modelling changes in electricity supply

From section 3.2.2 clear trade-offs between completeness and precision of the different models emerge. On the one hand, power system models give a more precise estimate of substitution within power plant types (e.g. marginal technologies affected by intermittent renewable energy). On the other hand, these models are not able to reflect the expansion of electrification to provide other energy demanding services such as transport or heat, as energy system models do. None of the above models include potential indirect effects induced in other markets such as indirect land use change or rebound effects. For that purpose, computable general equilibrium (CGE) models have been used (Dandres et al. 2011; Marvuglia et al. 2013) which in turn use very simplified models of the electricity sector. Figure 1 illustrates different potential applications of these models.

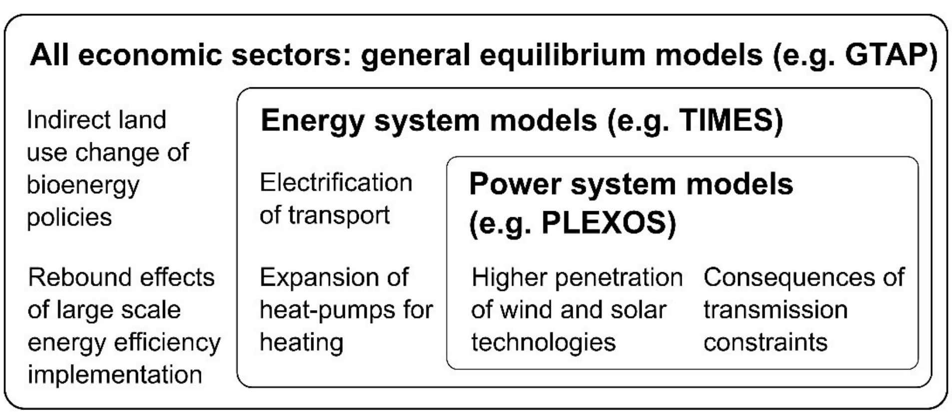

Figure 3.1: Different models comprising electricity supply: examples potential applications.

Given the tradeoffs, it is important to choose the type of model that best fulfils the needs of the analysis on a case-by-case basis. For studies where electricity is not the main source of environmental burden, generic inventories can be used. Attributional inventories are also less affected by temporal changes as average electricity mixes include the existing stock of power plants. If the aim is to inform national energy policies in long-term time horizons, partial equilibrium models such as the TIMES family are well suited. Based on cost optimization and being grounded on economic principles, these models can easily integrate the effect of environmental and economic policies such as carbon taxes, cap and trade agreements or subsidies. CGE models were conceived to study large (non-marginal) changes, and can be used to detect possible cascade effects in the global economy either through validation or soft linking (Vázquez-Rowe et al. 2014; Igos et al. 2015) helping to determine whether omitting inter-sectorial dependence is an acceptable simplification.

The large scope of energy system models becomes a disadvantage when it comes to time resolution, potentially undermining the precision of inventories. As discussed in section 3.2.2, time resolution is particularly important when assessing the need of dispatchable power plants. This limitation justifies the use of power system models in scenarios where flexible power plants are more solicited (e.g. considering substantial increases in the share of non-dispatchable technologies such as wind and solar). Power system models are also more suitable than energy system models to study inherent uncertainty of wind and solar generation and transmission constraints. Because power system models focus solely on the electricity sector, they can more easily perform the computationally demanding uncertainty and power flow analyses.

Retrospective analyses focus on past events, but are a useful tool to evaluate how electricity consumption mixes have changed over time and evaluate "what if" scenarios, with the advantage of being based on real data. Retrospective statistical models have also been used to identify marginal producing plants (EPA 2015) addressing the untraceability problem described in section 3.2.1

Economic optimization models have the advantage of naturally integrating the life cycle costs inventory, stepping towards life cycle sustainability inventories. For simplicity optimization models usually assume electricity markets operate under perfect competition, and thus participants have no market power and are not regulated. This assumption is questionable in oligopolistic and regulated electricity markets, which are not uncommon in the electricity sector (Lise et al. 2006). As an example, leading players like China, the world largest consumer of electricity, still relies on a considerably more complex multi-level dispatch hierarchy partially based on power plant output planning (Kahrl and Wang 2014). Oligopolies have been studied using game theory approaches (Lise et al. 2006; Pineau et al. 2011) but to our knowledge, game theory approaches have had limited use in LCA of the electricity sector. It should also be acknowledged that game theory approaches have difficulties in predicting marginal technologies (Pineau et al. 2011), especially since such approaches are more concerned with strategic behavior than empirical forecasts.

Nearly all the prospective models are considerably complex and require a substantial amount of data, which needs to be periodically updated. As a consequence many of them are proprietary models (Pfenninger et al. 2014), meaning that the underlying code or the data is not publicly available. This is an obvious problem for transparency and reproducibility that can be partially solved using open-source models. The TEMOA energy model constitutes a good example, designed for higher levels of transparency and reproducibility, all the code and underlying data are made publicly available for third party verification (Hunter et al. 2013). Nonetheless it is still up to question how publicly available models and associated databases can be maintained without substantial public funding.

3.3.2 Filling technology data gaps

In the absence of specific emission data from facilities, statistical inference techniques can be used to estimate emission factors and associated uncertainties. Using regression, emissions factors can be estimated from available data such as plant age, fuel type and country gross domestic product (see Steinmann et al. (2014b) for a case study on coal power plants). Alternatively, engineering models included in feasibility and pre-feasibility software such as WaSP or Retscreen can be used. These tools are more useful at the early stage of LCI or for validation purposes. Validation is especially relevant in cases where reported data is of doubtful quality. Statistical interpolation methods such as kriging have also been applied to complete electricity LCI, and appear to be superior to regression analysis (Moreau et al. 2012) but their application in LCI needs further validation. Caduff et al. (2012) provides a good example of how engineering models can be used together with regression analyses to fill inventory data gaps. The study analyzed retrospectively the gradual observed decrease over time in GHG emissions of electricity from wind turbines, which were partially attributed to a gradual increase in the size of the turbines but also to learning effects (Cadduf et al. 2012).

Hybrid inventories combining input-output and process-based data are also gaining precision. Namely, recent models such as THEMIS include 15 different technologies to model electricity (Gibon et al. 2015). The use of THEMIS has resulted in new insights, such as the importance of spare parts in offshore wind technology, upstream fugitive emissions and life cycle impacts of large-scale implementation of low carbon technologies (Arvesen et al. 2013; Bouman et al. 2015; Hertwich et al. 2015). Complementing process-based and input-output data is therefore an interesting approach to improve LCI completeness.

To account for technological change, the LCA community can use estimates from technology roadmaps and integrate them in energy system models. Agent-based models constitute an interesting alternative to address innovation, as they are designed to predict emergent behaviors (Pfenninger et al. 2014). The workshop on LCI of electricity held in 2001 concluded that data gaps of future technologies should be addressed using a conservative approach and thoughtfully documented (Curran et al. 2005). Moreover, Arvesen et al. (2011) argued that there is unrealistic technology optimism in climate change mitigation assessments. We encourage taking a conservative approach and test via sensitivity analysis the impact of such assumptions.

The integration of economic models increases substantially the data required to create dynamic LCI. For that matter, the rollout of smart grids can be very useful to better understand the demand side, although legitimate concerns about privacy will need to be addressed. The supply side has its own challenges, if consumers are concerned about privacy, utilities are generally reluctant to disclose market-sensitive information. In the short-term, initiatives such as the ENTSO-E (2016) transparency platform of the pan-European electricity market can be very helpful to improve our understanding of the electricity sector. The platform will provide data at different levels of aggregation, from generation units to bidding areas. The data spans from generation per unit to congestion management and year-ahead forecasts of load demand. Additionally, open-data peer-reviewed platforms (e.g. (Nature 2016)) could be used by researchers and industry to share common datasets. These opportunities remain unexplored and have potential to improve most of the data quality characteristics of LCI.

3.3.3 Structural changes in LCI

Several modelling opportunities are underpinned by updates in the data format of LCI. The upgrade of Ecospold to version 2 and the ILCD format provide capabilities that have not yet been fully exploited. Ecospold 2 allows to use more probability distributions during the uncertainty analysis, permitting the modeler to use the distribution that best fits the data (Weidema et al. 2013). A higher level of parameterization is possible for both formats, facilitating the exchange of parameterized datasets. Parameterization means that flows can be defined with formulas, as a function of other flows, or their properties (e.g. dry mass, heating value etc) instead of computed values (Cooper et al. 2012; Meinshausen et al. 2014). Parameterization eases the consistency, reproducibility and transparency of the datasets (Heck et al. 2009), and can be used together with engineering models to understand how systems will operate under new circumstances. Flows can also vary with the geographical location, which can be unequivocally identified in both formats. This feature is particularly powerful in Ecospold 2, as it allows a wider variety of geometrical descriptions, in line with the recommendations of the Shonan principles (UNEP, 2011). The potential to create geographically dependent environmental flows is particularly relevant for wind and solar technologies, whose performance depends on the weather. Importantly these 'meta-models' can be systematically enriched by a growing literature of studies, helping to understand whether different LCA results arise from technological or spatiotemporal reasons (Heck et al. 2009). For this to happen the key parameters (Table 3.3) need to be easily accessible and systematically reported per power generation technology. Databases such as ecoinvent or the European reference life cycle database (ELCD) (Joint Research Centre 2015) are moving towards parameterized datasets but to our knowledge, most of the software can only read parameterized datasets in ILCD format. Additionally, parameterized datasets are of limited to unit process data, and therefore of limited use when datasets are aggregated into system processes for confidentiality reasons.

Table 3.3: Key parameters of electricity production technologies required in meta-analyses.

Technology	Parameters	Source
Generic	Location, technological maturity, installation year, ISIC classification, period of validity, capacity, operating lifetime, capacity factor, technology type, data type (empirical or theoretical), plant production and decommissioning, characterization factors, efficiency.	(Warner and Heath 2012) (Weidema et al. 2013)
Wind	Wind characteristics (wind load hours), annual yield, weight, hub height.	(Caduff et al. 2012; Padey et al. 2012)

Photovoltaic	Solar irradiation, annual yield, mounting type, performance ratio, origin of cells and modules.	(Hsu et al. 2012)
Coal-fired	Combustion emission factors, coal type and characteristics, coal heating value, coal transport, coal mine CH_4 emissions.	(Whitaker et al. 2012)
Nuclear	Waste handling, uranium mining method, uranium ore grade, enrichment method, waste reprocessing.	(Warner and Heath 2012)
Hydropower	Latitude, organic carbon input, CH_4 from diffusion, ebullition and degassing, capacity, expected annual generation, area, volume, residence time.	(Barros et al. 2011; Hertwich 2013)
Gas-fired	Combustion emission factors, gas heating value, gas leakage, (additionally, liquid unloading and well completion if shale gas is used).	(O'Donoughue et al. 2014; Heath et al. 2014)
Solar thermal	Solar fraction, direct normal irradiance, efficiency, annual generation.	(Burkhardt et al. 2012)

Additionally, Ecospold 2 underpins the creation of CLCA datasets that are now available in the ecoinvent database for a wide range of countries. This facilitates the creation of CLCA analysis since electricity datasets are in the background of almost every service and product. Nonetheless, the data is partially of low quality and should be used cautiously (Treyer and Bauer 2014).

Despite the progress, modelers cannot take advantage of these features without the appropriate software development. In many cutting-edge aspects of LCA such as dynamic LCA, software lags behind and research groups have to create their own software (Pauliuk et al. 2015). As pointed out in this review and in the work of Pauliuk et al. (2015), open-source tools provide a good opportunity to fill this gap, and improve transparency and reproducibility in LCA.

3.4 Conclusions

This review summarizes key challenges and opportunities with respect to data quality of electricity supply LCI. Some of the challenges can be addressed with better, i.e. more consistent, comprehensive and transparent reporting, while others require the development of new methods, merging LCA with modeling approaches from other disciplines. Some of the proposed methods require software tools that are not currently available.

From all the challenges, modelling the temporal dynamics of electricity supply is probably the most complex given the number of tradeoffs. The integration with economic models offers great opportunities but none of the current models fulfills all the needs, presenting tradeoffs between completeness and precision. The selection of the type of model that best fulfils the aims of the study depends on several factors such as temporal, geographical and technological scope, market structure and data availability. Temporal dynamics are likely to be particularly relevant for technologies that operate intermittently, in peak times or very long periods. In such cases, the potential intra-annual and inter-annual changes on emissions should be considered in the evaluation of temporal representativeness.

With respect to reproducibility, meta-analyses of LCA studies on electricity production have systematically encountered poor reporting, hampering efforts to generalize conclusions. For that matter, consistent reporting of key parameters (Table 3.2) is recommended. Parameterized datasets of electricity production such as the ones available in ecoinvent ease reproducibility, transparency and consistency, as key “benchmark” parameters are directly available in the datasets and can be transferred and easily updated. The integration of LCA with economic models substantially increases data requirements, bringing additional problems of reproducibility and transparency unless these models are thoughtfully documented. Consequently, open-source models that allow third party verification should be prioritized.

Despite the great improvements in geographical coverage, some regions are still underrepresented, particularly African countries. In the absence of better data, statistical inference techniques and models designed for feasibility assessments can provide a first approximation and improve representativeness. Statistical methods provide less precise estimates, but can quantify associated uncertainty, minimizing the risk of misinterpretation.

At national scales, representativeness of current technologies is limited by the way national statistics are reported. The use of more detailed data where available (e.g. ENTSO-E transparency platform) should be explored to evaluate the benefits of having disaggregated data. Technology roadmaps and learning curves can be used to forecast changes in efficiencies of new technologies, but we advise to have a conservative approach and conduct sensitivity analyses.

Finally, we would like to see international reference institutions such as the IEA moving a step forward with respect to data disclosure. As noted before, results and underlying assumptions of the World Energy Model would be a very valuable benchmark, but to date are insufficiently reported.

CHAPTER 4 : METHODOLOGICAL PROBLEMS LINKING TIMES AND LCA MODELS, A REVIEW OF THE LITERATURE.

Avant-propos

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Contribution au document : révision des problèmes méthodologiques dans l'intégration des modèles TIMES et ACV, et comment ces problèmes ont été adressés dans la littérature.

Résumé :

La chaîne d'approvisionnement en énergie est l'épine dorsale des sociétés industrialisées, mais c'est aussi l'une des principales causes des impacts environnementaux mondiaux. La gestion du cycle de vie (GCV) et l'analyse du cycle de vie (ACV) sont de plus en plus utilisées en combinaison avec des modèles d'optimisation des systèmes énergétiques (MOSE) pour mieux représenter le secteur de l'énergie et sa dynamique et faciliter une meilleure prise de décision. L'intégration des MOSEs et ACV peut permettre des analyses puissantes, mais non sans difficultés. Dans ce chapitre, une revue des études liant un MOSE largement utilisé (TIMES) à des bases de données d'ACV est effectuée, les principaux défis sont identifiés et la manière dont ils ont été traités. L'identification de processus équivalents entre les inventaires de cycle de vie et les bases de données ESOM est l'un des principaux défis de l'intégration des deux types de modèles : c'est le problème

d’établissement de correspondances. D'autres problèmes tels que le double comptage et la cohérence des paramètres ont été identifiés et sont également étudiés.

Abstract

The energy supply chain is the backbone of industrialised societies, but it is also one of the leading causes of global environmental burden. Life cycle management (LCM) and life cycle assessment (LCA) are increasingly being used in combination with energy system optimisation models (ESOM) to better represent the energy sector and its dynamics, and facilitate better decision-making. The integration of ESOM and LCA can enable powerful analyses, but not without difficulties. In this chapter, we review studies linking a well-known bottom-up ESOM (TIMES) with LCA databases and identify the principal challenges and how they have been addressed. One of the main integration challenges is the identification of equivalent processes between life cycle inventories and ESOM databases: the mapping problem. Other concomitant issues such as double counting and parameter consistency have been identified and are also investigated.

4.1 Introduction

The economic growth observed in the last century has been heavily correlated with a sharp rise in energy use, improving living conditions for many, but also resulting in large environmental damage (Smil 2004). For instance, the energy sector is responsible for nearly two-thirds of global greenhouse gas emissions (IEA 2016). Therefore, there is an urgent need to transform the energy supply chain, decarbonising electricity supply and electrifying services traditionally reliant on fossil fuels (IEA 2016). Many stakeholders have a role in this transition, from businesses to governments and consumers. Stakeholders need tools to understand how the energy system is likely to evolve and how it may react to various decisions made within the system.

In this journey, life cycle management (LCM) can help to prevent burden shifting, but using it alone ignores the various energy dynamics. The use of energy system optimisation models (ESOM) together with life cycle thinking has the potential to underpin comprehensive understanding of the energy supply chain and its influence on sustainable production. There is a small but increasing number of studies combining life cycle assessment (LCA) and ESOM (Pietrapertosa et al. 2009; Choi et al. 2012; Daly et al. 2015; Menten et al. 2015; García-Gusano et al. 2016b, a; Hugues et al. 2016; Scott et al. 2016; Volkart et al. 2017; McDowall et al. 2018), ESOM best practices start to include LCM practices, such as goal and scope definition or the use of data quality indicators as a way to quantify epistemic uncertainty (i.e. the uncertainty associated with data quality) (DeCarolis et al. 2017). However, combining both models is not a simple task. In this chapter, we cover the challenges identified in the integration of ESOM and LCA, as well as existing approaches to address them and their limitations. For brevity, we focus on inventory level and do not cover impact assessment issues. Details of the criteria used to select articles are detailed in section 4.1.3.

4.1.1 Energy system models: origin and strengths

Energy infrastructure requires substantial investments and governments have used mathematical models for a long time to support policy analysis. The use of mathematical models can help understand the complex interactions that occur in the energy system, formalising the scattered knowledge about its dynamics (Pfenninger et al. 2014). Models of the energy sector grew in importance in the aftermath of the oil crisis of the 1970's. During that period the International Energy Agency was founded and started developing its ESOM. Broadly speaking, energy models follow two different paradigms, they either provide scenarios of how the system could evolve from a normative standpoint (optimisation models), or they attempt to forecast how the system is likely to change (simulation models) (Pfenninger et al. 2014). Optimisation models are better suited to analyse long-term scenarios (Loulou et al. 2005) and are therefore consistent with the common long-term temporal scope of LCA studies. This chapter focuses on bottom-up technology rich models. Principally the MARKAL / TIMES (The Integrated Markal Efom System) optimisation model generator developed by the International Energy Agency. TIMES is possibly the most widely used general purpose ESM (Pietrapertosa et al. 2009; Pfenninger et al. 2014). Alternative models following a similar structure such as TEMOA (Hunter et al. 2013) or OSeMOSYS (Howells et al. 2011) are also considered.

TIMES models are based on cost minimisation and provide consistent possible evolutions of the energy system under a set of user-defined constraints. These models provide insights to businesses and policymakers, as they allow exploring potential interactions which are difficult to foresee without a formal mathematical framework. TIMES models are "bottom-up" models, with often thousands of technologies competing to provide a given level of demand for energy services. The solution of the optimisation problem provides potentially useful results, such as capacity additions, activity levels or material and emissions flows for each technology. TIMES models use simplifying assumptions, such as perfect competition. Perfectly competitive markets maximise the total surplus, which is an indicator of social welfare (Loulou et al. 2005). Thus, although real situations deviate from perfectly competitive markets, the solutions can be used as a benchmark. Deviations from perfect competition conditions can be studied through specific constraints such as pre-defined market-shares or myopic foresight (Loulou et al. 2005; Glynn et al. 2015; DeCarolis et al. 2017). In contrast with general-equilibrium models, TIMES models assume partial equilibrium, which means that sectors outside the system's boundary are assumed not to be affected by changes in the system. For instance, prices of imports and exports outside the boundaries of the system are exogenously defined and not determined by the model.

4.1.2 Advantages of integrating ESOM and LCA

The advantages can be seen as an improvement in data quality aspects (ISO 2006b; Astudillo et al. 2017a). TIMES models tend to have a relatively limited scope for assessing environmental burden, often only tracking primary pollutants from operating energy-related infrastructure (Pietrapertosa et al. 2009; Glynn et al. 2015). Most of them ignore up-stream emissions associated with imports (Daly et al. 2015) or consumption of resources linked to energy use, such as freshwater (of importance for the growing literature on the so-called water-energy nexus (Kapsarc 2014; Pauliuk et al. 2017)). Moreover, they lack the detailed impact assessment methodologies used in LCM. The absence of a comprehensive environmental assessment can result in burden shifting and fail to identify potential co-benefits of environmental policies. Life cycle thinking has been instrumental in addressing burden-shifting in the energy sector (Hellweg and Milà i Canals 2014). For example, it was through LCA studies that the environmental impact of biofuels was better understood (Hellweg and Milà i Canals 2014).

TIMES models are also extremely useful for advanced life cycle studies, both for consequential and attributional approaches. TIMES explicitly model the future changes in the energy system, one of the major limitations of LCA (Pauliuk et al. 2017). The integration improves the temporal and technological representativeness, completeness and precision of inventories. TIMES also integrates economic considerations, which are fundamental in decision-making (Astudillo et al. 2017a).

4.1.3 Literature review

The integration challenges identified in this book chapter stem from our efforts linking the TIMES model NATEM with life cycle inventories (LCIs) (Astudillo et al. 2017c, b) and reading of associated literature. The existing approaches to address these challenges are based on a literature review. To identify potential articles, we used the search terms "LCA", "life cycle assessment", in combination with one of the following keywords: MARKAL, "TIMES model", OSeMOSYS, TEMOA, ESOM in the search engine Web of Science, covering publications of the last ten years. The keyword "TIMES" is too generic to be used as a meaningful filter. However, most of the publications mention the keyword MARKAL, the TIMES predecessor. To complete the review, we revised the annual summaries of the ETSAP, covering publications from 2005 until 2013 (ETSAP 2013). ETSAP´s reviews include over 250 references to articles using TIMES models in peer-reviewed journals. Studies deriving life cycle emissions from environmentally extended input-output (EEIO) data are included, despite having a different level of technological detail (Daly et al. 2015; Scott et al. 2016; McDowall et al. 2018). Only works presented in peer-reviewed journals were considered. Studies that used LCA data for comparative purposes but did not attempt to integrate inventories (e.g. (Frenette et al. 2016; Levasseur et al. 2017)) or that had unclear methodology with unrecheable authors (Tokimatsu et al. 2015) are not included in the review. Overall, ten articles are included in our analysis (Table 4.1). We note that prospective LCA of energy systems has also been done with other model paradigms such as general equilibrium models or power models (Astudillo et al. 2017a). However linking suchs models entails different problems and is out of the scope of this chapter.

Table 4.1: Scope and number of technologies mapped in studies integrating TIMES models and LCA

Sectors	Nº of tech. mapped	Scope	Database	Ref.
Norwegian electricity sector	9	attributional	ecoinvent 3	(García-Gusano et al. 2016b)
US electricity sector	9	attributional	US LCI and ecoinvent 2.2	(Choi et al. 2012)
Multisector (end-uses) and electricity sector (Switzerland)	43	attributional	ecoinvent 2.2	(Volkart et al. 2017)
Electricity and oil mining sector	7	attributional	ecoinvent 1.1	(Pietrapertosa et al. 2009)
Multisector	192	consequential	ecoinvent 2.2	(Menten et al. 2015)

Spanish electricity sector	26	consequential	ecoinvent 3	(García-Gusano et al. 2016a)
UK energy supply	250	not stated	UK EE-MRIO	(Daly et al. 2015; Scott et al. 2016)
EU electricity sector	146	not stated	Exiobase and ecoinvent	(McDowall et al. 2018)
French biofuel sector	35	not stated	mixed	(Hugues et al. 2016)

4.2 LCA-TIMES Integration Challenges

In TIMES models the energy supply chain is defined as a set of energy resources, conversion technologies and end-use demands connected by energy commodities in what is called the reference energy system (RES). The RES provides a complete description of the system boundaries and the level of technological detail of a model (Wene 1996). The RES is the equivalent to the product system in LCA (ISO 2006b). The level of technological detail can be similar to process-based LCI databases. Thus similar descriptions of the energy supply chain -from resource extraction to final use- can be found in both models. Linking ESM and LCI may seem straightforward, as both models share a similar structure, but these models are conceived to be used independently, and overlapping features can easily result in problems such as double counting (Menten et al. 2015; Volkart et al. 2017) or incomplete inventories. Faced with redundant information, the modellers need to choose which information prevails. The methodological choices may involve a trade-off between data quality aspects (Astudillo et al. 2017a) which should be considered in the goal and scope definition.

Softlinking implies associating elements of the two models. We will refer to the problem of associating elements of two different models as the "mapping problem". Several issues complicate the mapping problem. First, TIMES models often include thousands of technologies: making a one-to-one linking between LCI and TIMES processes almost infeasible. There are no general name conventions or ISIC codes that can be used to automate the linking, that still heavily relies on manual identification. Second, both models can track the same emissions (e.g. greenhouse gases (GHG)), and some linkages between processes are not explicitly modelled in TIMES (e.g. cement production and infrastructure development). Adding LCI in the model can easily result in double counting (Volkart et al. 2017). Third, consistently introducing life-cycle emissions in the optimisation problem often requires a one-to-one mapping of processes in TIMES and LCI's. For example, emissions from end-of-life treatment could be included in TIMES, but these are potentially different for each process. In most of the cases, a one-to-one mapping would be excessively time-consuming. Fourth, key parameters of processes such as efficiency or emission factors may differ between models, which can result in inconsistencies. Last, if multifunctional processes are within the system boundary, the allocation should be avoided using system expansion (ISO 2006b). However, this is hardly discussed in the literature.

4.3 Existing approaches to address the integration challenges

4.3.1 Mapping TIMES-LCA processes

The "too many processes" issue preventing a one-to-one mapping is one of the most complicated integration problems. This issue has been addressed using two simplifications: limiting the scope of the assessment to specific parts of the energy supply chain and representing sections of the supply chain by their aggregated LCI or LCA indicator.

The integration efforts reviewed used multisector TIMES models, but most of the studies limit their scope to attributional studies of the electricity sector (Table 4.1) and do a partial integration. Several studies use market mixes from TIMES for prospective assessments, improving temporal representativeness (Choi et al. 2012; García-Gusano et al. 2016b, a), others integrate life cycle emissions in TIMES models (Pietrapertosa et al. 2009; Daly et al. 2015; Hugues et al. 2016; Scott et al. 2016; McDowall et al. 2018). Limiting the boundaries to a particular sector reduces the number of technologies that need to be mapped, but it could result in a loss of completeness, questioning the suitability of the system boundary. For example, Choi et al. (2012) used multisector MARKAL model to update a prospective electricity mix in the US for different scenarios such as cap and trade or CO_2 taxes. However, such policies affect more than just the electricity sector, and induced changes in other sectors of the model should be considered to make a fair comparison of different scenarios. Ref (Pietrapertosa et al. 2009; Daly et al. 2015; Hugues et al. 2016; Scott et al. 2016; McDowall et al. 2018) added life cycle emissions to several processes of a MARKAL/TIMES model to internalise environmental emissions. It was a first step towards the integration of externalities, but incomplete mapping may be problematic as it may induce a bias against the mapped technologies (see section 4.3.3). Volkart et al. (2017) improved completeness, assigning life-cycle impact scores to all end-uses of all sectors. In this case, there is a wider range of processes that deliver the energy services (heat, transportation, etc.), raising the number of equivalent processes required (Table 4.1). The study used end-use technology mixes and energy demands from TIMES. However, the technology mixes and efficiencies for "non-end-use" processes (such as electricity generation) were selectively updated. The authors recommended using a more consistent approach in future research (Volkart et al. 2017). Indeed, upstream processes may also change over time or between scenarios (e.g. switch from conventional to unconventional gas or feedstock from biofuels). These changes should be identified in a systematic manner.

The approach of limiting the boundaries to a particular sector is more difficult to justify in consequential studies since all the processes that are expected to change should be included (Astudillo et al. 2017a, c). Changes can be induced by market or policy effects. Our experiments using a TIMES model of a relatively small region (Quebec, Canada) indicate that a large proportion of the processes change their output to some extent (Astudillo et al. 2017d). The best example of a consequential study using TIMES and LCA was an analysis of the effects of introducing biodiesel from biomass in France (Menten et al. 2015). In this case, all technologies in the TIMES model were mapped (192). This approach produced a complete mapping, but it may be unfeasible with larger TIMES models, which can easily contain thousands of technologies.

We have recently proposed to use a cut-off criterion, that is, to exclude a percentage of the material and energy flows based on their contribution to an indicator measured in TIMES (e.g. CO_{2eq} emissions) (Astudillo et al. 2017d). The cut-off can help to discern the most relevant changes, reducing exponentially the number of processes that need to be mapped (Astudillo et al. 2017d). Nonetheless, it introduces some other problems, such as the possibility of omitting processes with high impacts in other areas of concern but low CO_{2eq} emissions.

4.3.2 Double counting

Double counting problem is hardly discussed in the literature of TIMES-LCA linking (Volkart et al. 2017). Part of the energy and emissions considered in TIMES models is used to deliver intermediate products that are already accounted in LCI, resulting in double counting (Menten et al. 2015; Volkart et al. 2017). For example, the output of the cement sector is typically considered independent of other demands in TIMES models but will be used to build the infrastructure that is already included in LCIs. As pointed by Menten et al. (2015), this can be mitigated by presenting relative results between scenarios, where double counting effects cancel out, to some extent. This limitation is not exclusive of TIMES models. A recent review of integrated assessment models stated that most of them miss linkages related to infrastructure and ignore material cycles, which are the fundamental characteristics of the life cycle perspective (Pauliuk et al. 2017). Constructing more "circular" RES in TIMES models is challenging, as the models need to be calibrated using national statistics, and these do not necessarily have a high level of detail of material flows leaving each sector. Studies linking TIMES with EEIO data have more thoughtfully addressed double counting, erasing manually repeated areas of the inventory (Daly et al. 2015; Scott et al. 2016; McDowall et al. 2018). McDowall et al. (2018) used fixed input-output coefficients to adjust the exogenously defined demands (e.g. the steel demand from energy technologies is used to adjust the energy demand of steel production). Ideally, these demand corrections would be calculated endogenously by the TIMES model, but that would require substantial additional linking of processes.

4.3.3 Integrating life cycle emissions in the optimisation problem

Several of the reviewed publications integrated LCA data into the optimisation algorithm, but only for some parts of the energy system (Pietrapertosa et al. 2009; Daly et al. 2015; García-Gusano et al. 2016b; Hugues et al. 2016; Scott et al. 2016; McDowall et al. 2018), with the risk of introducing a bias. A consistent integration of life-cycle emissions into the optimisation problem is challenging, as it will bias the assessment towards sectors where accounting of emissions is less complete. Garcia-Gusano et al (2016b) noted that imposing limits on LCA scores for electricity generation greatly affected trade balances against local production, as trade processes did not have emissions associated. Consistently including emissions for all processes in a TIMES model (e.g. end-of-life burdens) would require a one-to-one mapping, which is extremely time-consuming in large TIMES models. Alternatively, large TIMES models can include emissions if it is for a limited number of processes. For example, a model dealing with operating GHG emissions could include emissions from gas distribution or refrigerant leaks or electricity imports (e.g. (ETSAP 2013)) without losing consistency. Ultimately, TIMES results should be interpreted while taking into account potential inconsistencies and lack of completeness of the inventories. Refs. (Daly et al. 2015; McDowall et al. 2018) are good examples, as they provide guidance on how to interpret results and what kind of conclusions could not be drawn.

4.3.4 Technological representativeness

TIMES inventories represent future supply chains, while most of the LCI data are from current supply chains. Parameters such as efficiency, capacity factors or emission factors of the same technology may therefore differ. Unless a harmonisation step is introduced, the integration could lead to inconsistencies. The level of consistency in the different integration is difficult to evaluate because, with some exceptions (e.g. (Daly et al. 2015; Volkart et al. 2017)) it is not well documented and rarely discussed. Studies using EEIO data acknowledge that sectoral aggregation is an additional problem, as sectors with different emission intensities can be grouped together, eroding data representativeness (Daly et al. 2015). Garcia-Gusano et al. (2016b) suggested learning from the experiences linking bottom-up and general equilibrium models (Wene 1996). Some of the concepts developed during other integration efforts can be applied to the integration of TIMES models and LCA databases. For example, the introduction of common measurement points (i.e. points where both models have the same result) would be useful to formalise the soft linking approach.

4.3.5 Dealing with multifunctional processes

Multifunctional processes should be handled in a way that is consistent with the scope of the analysis and if possible, avoiding the allocation using system expansion (ISO 2006b). However, except Menten et al. (2015), studies do not specify how allocation has been conducted when it could not be avoided (e.g. one of the outputs being outside the system boundary).

4.4 Discussion and conclusions

The TIMES-LCA integration is clearly in expansion, with several recent publications on the topic. Integration can range from a very simple level (e.g. identification of future average or marginal technologies in a particular energy market), to more detailed ones, capturing market and policy interactions and transformations in the entire energy supply chain. More comprehensive approaches also imply a substantial additional effort, particularly solving the mapping of processes between the two bottom-up models.

To date, the existing literature has focused on attributional studies of electricity generation, although some multisector and consequential studies exist. Limiting the scope to part of the system may miss important changes outside the chosen system boundaries. The potential lack of completeness needs to be considered in the definition of the goal and scope. The truncation of the system boundary is especially unwarranted for consequential studies, where limiting the scope to specific sectors would result in an incomplete inventory.

TIMES and LCA often have overlapping representations of the supply chain, and modellers have to choose which data prevail, substituting parts of the TIMES representation by LCA counterparts. Direct substitution entails the risk of missing important changes across the supply chain. Therefore, the need for systematic approaches to prioritise which LCI data should be updated. The ordering of processes and application of a cut-off based on a criterion such as CO_{2eq} emissions can help to both identify relevant changes and reduce the number of processes to be mapped.

Consistent linking requires also updating parameters such as efficiency and emission factors. Integration efforts outside the LCA field suggested already in 1996 to use common measurement points, unambiguous measurement points where the two models should yield identical results (Wene 1996). The formalisation of these points implies a harmonisation of parameters, and the assessment of the extent by which both models measure the same phenomena and the same future (Wene 1996). The author also pointed out the need to share a common formalised language between models (Wene 1996). The specification of such conceptualisation is called ontology, a field of growing interest in industrial ecology and recently discussed in the LCM conference (Vandepaer and Gibon 2018). The need for more traceable and transparent workflows that go beyond the common reporting on scientific articles was also stressed (Vandepaer and Gibon 2018). We agree, as articles often don't offer sufficient explanation to understand the details of how the linking was done.

The process of linking models goes beyond solving the implementation problem (Wene 1996). It is also an opportunity to learn about the system and the implications of different perspectives, which are essential to interpret results. LCA modellers should consequently keep in mind the underlying assumptions and values of ESOM.

CHAPTER 5: EXPLORING GLOBAL WARMING MITIGATION OPTIONS IN QUEBEC WITH A TIMES MODEL

Avant-propos

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Titre en français : le secteur résidentiel peut-il réduire les couts d'atténuation du réchauffement climatique? Étude de la sensibilité du modèle techno-économique TIMES à des paramètres clés.

Contribution au document : adaptation du modèle NATEM pour répondre aux questions de recherche.

Keywords: TIMES, peak load, heating, climate change, hydropower, open data,

Résumé :

La transition vers des sociétés à faibles émissions de carbone pourrait augmenter la demande de pointe en électricité, ce qui peut coûter cher en énergie renouvelable, dont la disponibilité est incertaine. Les bâtiments sont souvent la principale cause de la demande de pointe. En parallèle, il semble qu'ils possèdent un important potentiel d'efficacité énergétique non exploité. S'il était exploité, ce potentiel pourrait considérablement réduire les coûts de transition vers des sociétés à faibles émissions de carbone, en réduisant les demandes d'électricité moyennes et maximales.

Nous explorons ce potentiel dans plusieurs scénarios de réduction des gaz à effet de serre en utilisant un modèle d'optimisation de système énergétique multi-secteurs TIMES développé pour la province de Québec pour la période 2011-2050. Les mesures de chauffage et de conservation

dans le secteur résidentiel sont modélisées à l'aide de simulations de bâtiments et des valeurs tirées de la littérature. La disponibilité intra-annuelle d'énergie renouvelable et d'importations d'électricité est tirée d'une analyse de séries temporelles. De plus, l'influence de paramètres clés tels que les projections de la demande en énergie primaire et les émissions résultant de la création de réservoirs hydroélectriques est également évaluée. Finalement, nous discutons des obstacles qui pourraient entraver la transition énergétique et de la manière de les surmonter.

Les résultats indiquent que la demande de pointe pourrait augmenter de 30% en raison des efforts de réduction des gaz à effet de serre, mais que cette demande de pointe peut être efficacement réduite par des interventions dans le secteur résidentiel. Les pompes à chaleur constituent la technologie de chauffage la plus rentable, malgré leur moindre efficacité dans les climats froids. Des enveloppes de bâtiment mieux isolées jouent un rôle important dans les nouvelles maisons, réduisant de 14% les coûts réduction de gaz à effet de serre, suggérant que les codes du bâtiment pourraient être plus ambitieux. Le scénario qui modélise une urbanisation plus dense entraîne des coûts de réduction des gaz à effet de serre beaucoup plus bas, ce qui souligne l'importance de la planification urbaine et des évolutions potentielles de la demande. Les changements observés dans cette étude se basent sur la tarification des services énergétiques sur la base des coûts marginaux et sur un comportement d'optimisation des coûts, et sont moins susceptibles de se produire avec les barrières de marché actuelles. Finalement, les émissions provenant de la création de réservoirs modifient l'ordre d'approvisionnement en électricité, favorisant les centrales au fil de l'eau et laissant suggérer que ces émissions devraient être prises en compte dans des scénarios de transition vers des systèmes énergétiques a faible empreinte carbone.

Abstract

The transition to low carbon societies may increase peak electricity demand, which can be costly to supply with renewable energy, whose availability is uncertain. Buildings are often the main cause of peak demand, and they are believed to hold a large unrealised energy-efficiency potential. If realised, this potential could considerably mitigate the transition costs to low carbon societies, reducing average and peak electricity demands.

We explore this potential in several cost-optimal global warming (GW) mitigation scenarios using a multi-sector TIMES energy system model of the province of Quebec for the period 2011-2050. Heating and conservation measures in the residential sector are modelled using building simulations and parameters' values from the literature. The intra-annual availability of renewable energy and electricity imports is derived from time-series analysis. Additionally, the influence of key parameters such as the projections of primary energy demand and emissions from reservoir impoundment is evaluated. Finally, we discuss some of the barriers that could hamper the energy transition and how they can be overcome.

Results indicate that peak demand would rise by 30% due to GW mitigation efforts, but it can be effectively reduced by interventions in the residential sector. Heat pumps are the most cost effective heating technology, despite their lower efficiencies in cold climates. Better-insulated building envelopes have an important role in new houses, reducing by 14% the GW mitigation costs and suggesting that building codes should be more ambitious. The scenario considering denser urban developments has much lower GW mitigation costs, underscoring the importance of urban planning and potential changes in demand. The observed uptakes are contingent to the pricing of energy services being based on marginal costs and cost-optimising behaviour, and are less likely to take place with current market barriers. Finally, the emissions from reservoir creation alter the merit-order of electricity supply, favouring run-of-river power plants and suggesting that these emissions should be considered in GW mitigation scenarios.

5.1. Introduction

To avoid the worst effects of anthropogenic global warming (GW) deep changes are needed in the energy system. The GW mitigation pathways pass by a gradual electrification of energy services previously provided by fossil fuels, and a decarbonisation of electricity supply (IEA 2013a). Buildings represent the largest energy-consuming sector in the global economy (IEA 2013a) and space heating is often the single largest source of energy needs in buildings. For instance, in cold countries heating accounted for 45% of energy demands in buildings in 2010 (IEA 2013a). Heating demand is also strongly seasonal, therefore higher levels of electrification would increase electricity peak demand unless demand-side measures are taken. Moreover, peak electricity can be increasingly complicated to supply with non-dispatchable renewable energies (Deane et al. 2015), which are expected to have an important role in future electricity supply (IEA 2013a, 2014c). In this context, reductions in electricity consumption in buildings can result in huge savings in electricity provision, avoiding capacity additions (IEA 2013a). According to the International Energy Agency (IEA) projections, buildings host the largest share of unrealised energy efficiency potential, mostly unexploited due to market barriers (IEA 2014c).

The analysis of the situation of the province of Quebec (Canada) can provide interesting insights into this problem, as it has some of the characteristics that future energy systems may have. Quebec already has a decarbonised electricity mix, with estimated average emissions of 22 Kg CO_2 MWh-1, much lower than the world average (520 Kg MWh-1 (Ang and Su 2016)). Quebec already has an important winter peak demand, 52% of the heating energy consumption is in the form of electricity, mostly from electric resistance systems (NRCan 2013), representing nearly 50% of electricity demand during the winter peak (Fig. A3 in supplementary material (SM)). Quebec has ambitious plans to "decarbonise" the economy, and it is committed to reducing by 37.5% and 80% its greenhouse gas emissions (GHGe) for 2030 and 2050 respectively, compared to 1990 levels (Trottier energy futures project 2016). It also has some distinctive characteristics; the electricity mix is dominated by hydropower, whose emissions are to date not yet fully understood (Barros et al. 2011; Scherer and Pfister 2016a) and often assumed to be negligible (Farhat and Ugursal 2010; IEA-ETSAP 2010). It also has one of the lowest electricity prices in the residential sector in North-America, partially due to historically low generation costs and cross-subsidies (Pineau and Langlois-Bertrand 2016), which can cause underinvestment in energy efficiency (Guler et al. 2001; Gamtessa 2013). Altogether, Quebec may be holding a significant unrealised potential for energy efficiency.

5.1.1. Assessments based on housing stock models

Several articles have covered the energy, economic and GHGe savings potential of Canadian households, including Quebec. Tamasauskas et al. studied the life cycle costs of cold-climate heat pumps (Tamasauskas et al. 2013), geothermal heat pumps and improved building envelopes in Montreal. The study found large potential energy savings (up to 70%) but with small life cycle cost savings. A set of publications examined the energy and GHGe savings of more advanced systems such as solar-assisted heat pumps (Asaee et al. 2017), solar combisystems (Asaee et al. 2016), solar water heating (Nikoofard et al. 2014a) and phase-change materials for energy storage (Nikoofard et al. 2014b). They did so using a housing stock model that has several components. A building energy simulation software is used to estimate energy savings, and it is linked to a database of households characteristics of single-detached & double/row houses in Canada (CSDDRD) (Swan et al. 2009). This database has a detailed account of the characteristics of around 17000 Canadian households and provides realistic estimates of the potential energy savings of different interventions. Housing stock models have the additional advantage of being able to identify technical constraints to the implementation of new technologies (Nikoofard et al. 2014a, b, Asaee et al. 2016, 2017).

However, housing stock models have some limitations when it comes to assess GHGe and cost savings. When alternative systems were compared against the common baseboards systems in Quebec, GHGe savings are estimated using monthly short-term marginal emission factors of electricity (Farhat and Ugursal 2010). These emission factors are grounded on the assumption that hydropower is the most often affected marginal technology in Quebec, assigning a CO_2 marginal emission factor of nearly cero for Quebec for most of the months, which would discourage energy efficiency measures and changes in heating equipment as a GW mitigation policy. This contrast with IEA recommendations of preventing the use of electric resistance heaters as the main heating source (IEA 2013a). Nonetheless, regions as Quebec, with large hydropower capacity, can store energy resulting from energy efficiency measures and export it if transmission lines are not congested. Indeed, analysis of electricity trade data shows how exports from Quebec have avoided an equivalent to 7% of its emissions annually (Amor et al. 2011). If transmission lines are congested, new lines can be built, or electricity can be used to electrify other sectors such as industry and transport. Therefore, a long-term multi-sector approach may be better suited to identify opportunities for GW mitigation, particularly those where policy interventions are needed, such as infrastructure development.

From the aforementioned studies, the ones that conducted an economic evaluation did it using current electricity tariffs, which are useful to explain the financial viability from the homeowner's perspective. However, this approach fails to identify the potential savings at a societal level. Quebec has regulated tariffs, which do not cover the marginal costs of supplying electricity in winter. Hydro-Quebec, the government-owned utility that provides electricity in the region, regularly evaluates the "avoided costs" (i.e. marginal costs) of using electricity for heating, and they are considerably greater than current tariffs (Hydro Québec 2015). Therefore, an assessment using marginal costs, rather than current prices, can be useful to identify desirable strategies from a societal perspective.

The limitations of housing stock models were summarised by Kannan and Strachan (2009) as follows:

i) They do not account for details of costs.

ii) They ignore interactions in emission reduction opportunities with other sectors.

iii) They need exogenous assumptions of CO_2 emissions from electricity production.

5.1.2. Assessments based on energy system models

An alternative approach for assessing the potential savings in the residential sector, factoring the costs of peak demand, is to use long-term optimisation energy models such as those based on the TIMES paradigm. These models consider long-time horizons and assume marginal cost pricing, which results in a minimization of total system costs. TIMES is a model generator that has an internal representation of different sectors interconnected by energy commodities. These models allow analysing potential interactions between different sectors and regions, widening the scope of the possible solutions. Constraints can be imposed to the optimisation problem, which is very useful to identify GW mitigation strategies. The following subsections review the body of the literature on TIMES models that we found relevant for this study. We focus on the modelling of the residential sector and the generation of electricity from renewables, which is of growing importance in decarbonisation scenarios.

Modelling the residential and electricity sectors

The residential sector has some distinctive characteristics that need to be addressed in energy system models. One of them is heterogeneity; the sector is composed of different housing types, with different building envelopes and located in colder or warmer areas within the region under study. These factors affect the type of technologies that can be implemented and their efficiency, hence, having geographically and temporally representative data is challenging. Typically, MARKAL/TIMES models use between 1 to 6 housing types (Dodds 2014), although specific studies on behaviour heterogeneity have gone much further (Cayla and Maizi 2015). A study on the effects of disaggregation compared the effects of passing from 2 to 36 housing types and found small differences in the results (Dodds 2014). The study concluded that more aggregated versions are usually sufficient (Dodds 2014). Temporal representativeness represents another challenge. The intra-annual variation of demand, driven by heating and cooling is another distinctive feature of the sector (Fig. A3). A study combining a power system model with a TIMES model and a housing stock model emphasised its importance, as there could be important mismatches between renewable energy availability and energy demand (Deane et al. 2015). The importance of temporal disaggregation has also been emphasised in a recent analysis of best practices on energy system modelling (DeCarolis et al. 2017). Several studies (Dodds 2014; Cayla and Maizi 2015; Deane et al. 2015; Petrovic and Karlsson 2016; Merkel et al. 2017) identified heat pumps as one of the most relevant technologies, but their efficiency, as for solar technologies, depends on regional temperatures. Therefore, the efficiency of these heating technologies needs to be adapted from region to region. However, the adaptation is rarely discussed in the literature. For instance, there are no studies considering cold-climate heat pumps. Some studies have addressed the potential benefits of changing building envelopes (Dodds 2014; Deane et al. 2015; Merkel et al. 2017), but to the best of our knowledge, no study has taken into account the characteristics of the building envelopes to estimate the associated energy savings and costs. The characteristics of the existing building envelopes are important, as energy savings have a non-linear relation with increasing insulation levels.

With respect to electricity supply, it has been shown that TIMES models tend to underestimate the need for peak power plants due to their relative coarse temporal resolution (Kannan and Turton 2013; Deane et al. 2014). However, this is less problematic in regions endowed with plenty of trade options or dispatchable dam hydro resources (Kannan and Turton 2013). Quebec has plenty of hydro reservoirs, but to our knowledge, the availability of electricity from imports to cover peak demand has not been studied in detail. The availability of renewables is also an important issue. Some studies explicit the modelling of the intra-annual availability of renewable resources, typically wind and solar. A study on flexible time slicing used wind projection forecasts to model wind generation and sunrise and sunset hours for solar power (Kannan 2011). Another study of France's renewable potential, modelled availability of wind and solar resources using one year of data of electricity generation (Krakowski et al. 2016). There is less consensus on how to model hydropower. Hydropower has been modelled at annual (Lind et al. 2013; Krakowski et al. 2016) but also at seasonal or daily (Kannan and Turton 2013) levels, and the distinction between the availability of run-of-river and reservoir hydropower is rarely mentioned.

Modelling of human behaviour

Results from optimisation models are not forecasts, as human behaviour often differs from cost-optimal decisions found in energy system models. The divergence between human and optimised behaviours applies in particular in the household sector, where market barriers and heuristic thinking are common (Maruejols and Young 2011; IEA 2013a; Burak Gunay et al. 2014; Frederiks et al. 2015). Results of optimisation models can be unrealistic, displaying sudden technological changes ("bang-bang effects") and deviations from observed technological uptakes (Cayla and Maizi 2015). In TIMES models this is often approached imposing constraints to technology uptake and high discount rates in certain sectors (DeCarolis et al. 2017). In TIMES models focusing on behaviour heterogeneity, segmentation is used to model purchasing behaviour according to, e.g., income and ownership status (Cayla and Maizi 2015). However, as noted by a review of best practices, modellers may add constraints in order to make the results conform to their preconceived notions of how the future should unfold (DeCarolis et al. 2017). Therefore assumptions should be actively questioned, supported by empirical evidence and carefully documented (DeCarolis et al. 2017).

Behavioural changes can also mean changes in the demand for primary energy services. Energy system models typically segment demand in different final "commodities" (e.g. household heating for detached houses, apartments, etc.) and project the demand for these commodities according to exogenously defined drivers. For example, the growth in demand for household heating could be assumed to be proportional to a projection of the observed growth in the surface area of particular building types. Therefore, under a typical configuration, energy system models per se would not identify the potential benefits of changing functionally equivalent services. For example, denser urban areas with less detached houses and more apartments could result in lower mitigation costs. Therefore the mitigation pathways depend on what we consider to be substitutable. Some studies have assessed possible changes in demand, for example, Pye and Daly endogenised modal shifts in transport choices in an energy system model, similar to the TIMES-models (2015). Nonetheless, the analysis of changes in the demand for energy services is still relatively uncommon.

Modelling of emissions

Hydropower

Emissions from hydropower are typically considered negligible (Farhat and Ugursal 2010; IEA-ETSAP 2010). However, CO_2 and CH_4 emissions arise from the decomposition of submerged biomass and estimates of net CO_{2eq} emissions can widely vary. Emissions vary with age, location, morphometric features and chemical status (Barros et al. 2011). Recent modelling asserts that the carbon footprint is larger than previously assumed, and estimate emissions as high as 436 Kg CO_{2eq} MWh-1 for Churchill Falls (Scherer and Pfister 2016b), a shallow reservoir under the control of Hydro Quebec. The emissions attributed to Churchill Falls fall within the range of emissions from gas power plants and call for a deeper analysis in the design of low carbon futures.

Electricity trade

Emissions associated with the production of imported electricity are often neglected in energy system models (Daly et al. 2015). Nonetheless, neglecting these emissions in regions with limits on GHGe can induce the displacement of emissions to other non-regulated regions (Bushnell et al. 2014). When considered, emissions from imports have proven to be very relevant. Daly et al. (2015) modelled them combining a TIMES model of United Kingdom with an input-output model, and the inclusion roughly doubled the marginal abatement costs.

5.2. Material and methods

5.2.1. Goal and scope

The main goal of the analysis is to identify cost-effective GHGe mitigation opportunities in the residential sector in a region that already has a low-carbon electricity supply. We hypothesise that the benefits of interventions in the residential sector will become apparent when the long-term cost of supplying peak demand in a GW mitigation context is considered. A cost-optimisation long-term energy system model allows identifying desirable investments, but a number of factors need to be taken into account . First, many of the technological options of low carbon societies increasingly rely on renewable energy sources but these vary regionally. Therefore, the assessment needs to take into account the influence of regional climates on the availability, variability and efficiency of these technologies. Second, the characteristics of the housing stock need to be considered, as well as potential shifts from building types or envelopes. Both measures would improve the technological representativeness of the model. Third, possible sources of emissions such as hydropower reservoir creation and electricity imports may play an important role, and including them would render a more complete account of GHG emissions. Fourth, alternative uses of electricity such as electric transport need to be considered to identify the best allocation of available resources. These factors can be effectively assessed soft linking energy system models with results from other approaches such as building simulation or time series analysis.

The time horizon chosen is 2011-2050, since the GW mitigation commitments are set for 2050. The analysis focuses on the province of Quebec, but trade with each of the neighbouring regions is explicitly modelled to account for trade opportunities (Amor et al. 2011). Special attention is given electricity imports from Newfoundland and Labrador, from where a large share of electricity imports is coming. This study does not model the likely changes in the system due to rising temperatures induced by GW. Instead, some of the insights gained in similar regions (Minville et al. 2010; Seljom et al. 2011) are included in the discussion.

In this study, it is not our intention to forecast future technology uptakes but rather to analyse what would be the rational choices under cost optimisation and existing technical and legal constraints. Therefore, we focus on technological constraints rather than "behaviorally realistic" technological uptakes, which consider non-costs factors (Dodds 2014). Therefore, we did not impose higher hurdle rates or technology growth rates in the sectors under study. The technological constraints are described in more detail in the annex A. The model can result in uptakes that are unparalleled by historical uptakes, but they do represent the cost-minimising pathways, which are useful societal benchmarks. Results should be interpreted as technologically-plausible cost-optimal pathways subject to the technical and legal constraints and not as forecasts of what is likely to happen. The results can be used to identify mitigation opportunities and areas where market failures may be hampering cost-effective mitigation actions. As the IEA indicates, public policies are essential to help overcome issues such as split incentives, internalisation of environmental costs and high initial investments (IEA 2013a). As other scholars have emphasised, policy-relevant conclusions can rarely be extracted from results alone (DeCarolis et al. 2017). Thus we focus on insights and trends, analysing the results in the light of the limitations of the model. To the best of our knowledge, there are no other studies with a similar scope.

The analysis uses NATEM-Quebec, a simplified version of the North America TIMES Energy model, circumscribed to the province of Quebec. The model is summarised in the following sections. Section 5.2.2 covers its general characteristics, Section 5.2.3 the definitions of primary energy demand, Section 5.2.4 the modelling of the residential sector. Section 5.2.5 describes the modelling of the supply side, particularly the electricity provision with renewables and the electricity trade. Details of the modelling of the remaining sectors are provided in the annex A. The definition of the scenarios is detailed in section 5.2.6.

5.2.2. NATEM-Quebec – general characteristics

NATEM-Quebec is a technology-rich model of the energy system of Quebec, driven by 65 final demands across five sectors. It is a simplified version of NATEM, the version covering the entire Canada (Trottier energy futures project 2016; Vaillancourt et al. 2017). The model includes the energy supply chain, from extraction to final use. As other TIMES models, NATEM-Quebec simulates the market equilibrium under perfect competition, finding the investment and operation levels that minimise system costs. The model has more than 2000 technologies and 320 commodities interconnected, representing the supply and demand of energy as well as its associated GHGe. NATEM-Quebec tracks CO_2, N_2O and CH_4 emissions associated with energy use. GHGe are aggregated into CO_{2eq} emissions using global warming potential values over a time horizon of 100 years. Each technology is characterised by a series of parameters, such as efficiency, emission factors, investment costs and availability factors (AF). All investments are subject to a discount rate of 5%.

The model covers the period 2011-2050, with shorter time periods (2-3 years) for the beginning of the time horizon and longer ones (5 to 10 years) afterwards, a common practice in models with flexible time slicing (DeCarolis et al. 2017). Each year is divided into four seasons and each season in four intraday periods: day, night, morning peak and evening peak, resulting in 16 time-slices per year. The time-slices were chosen according to observed profiles of aggregated demand of electricity in the region (see Fig. A5 in annex A). This temporal resolution is commonly used in energy system models (DeCarolis et al. 2017) and should be sufficient, since regions with plenty of dispatchable dam hydro resources are less prone to errors due to low temporal disaggregation (Kannan and Turton 2013). Nonetheless, additional constraints are imposed to technologies with high stochastic uncertainty. The simplifying approach results in a lightweight model that can be solved in less than 2 minutes on a standard laptop, facilitating the iterative process of refining the research question and conducting sensitivity analyses.

5.2.3. Demand for energy services

NATEM, as other partial equilibrium models, uses exogenously defined demands for energy services, which are projected through the simulation period (Vaillancourt et al. 2017). In the current version, demand projections come from the Canadian Energy system simulator model (CanESS) (Whatif 2015). CanESS is calibrated with national historical statistics (Statistics Canada 2017) for the period 1978-2010 and the projections of the National Energy Board (2013). Small adjustments for Quebec have been made based on the results of the medee model. These projections represent what can be considered as a business as usual (BAU) scenario, characterised with a modest population and economic growth, but high growth in some sectors (Trottier energy futures project 2016; Vaillancourt et al. 2017). The segmentation of energy services by sector is detailed in annex A.

To study the potential savings associated with better urban planning, this study uses an alternative projection of the demands for energy services (Fig. A13). These projections stem from a previous assessment of challenges and opportunities to conduct major reductions on GHGe in Canada

(Trottier energy futures project 2016). The multi-stakeholder assessment recognised the considerable scope for making urban regions more functional and efficient through e.g. urban densification and modal changes in urban transport. Indeed, previous studies have found that denser developments have lower GHGe per capita (Norman et al. 2006). In the household sector, the improved urban scenario assumes that less single detached houses and apartments will be built with respect to the baseline projections, compensated by an increase of new attached houses. These changes result in a net decrease 10% of household heating demand with respect to the rest of the scenarios. In transport, it expects an increase of use of subways and inter-city rail transport, substituting passenger cars. The final demands of industrial, agricultural and commercial sectors remain unchanged. A summary of the changes is provided in Fig. A13. The changes were implemented in NATEM-QUEBEC, redefining the original projections of demand used in the rest of the scenarios. More details and underlying assumptions are available in associated literature (Boston consulting 2015; Trottier energy futures project 2016).

5.2.4. Residential sector

In NATEM-Quebec the residential sector is divided into single detached houses, attached houses, apartments and mobile homes, following the level of disaggregation of national statistics (Vaillancourt et al. 2017). Detached houses represent most of the heating demand (66%) followed by apartments (25%) and attached houses (11%) (NRCan 2013). The following subsections detail the modelling of the residential sector.

Availability factors

The AF measures the maximum fraction of energy that can be delivered by a technology with respect to their annual capacity. AF of heating equipment are hardly discussed in the TIMES literature, but they can play an important role in investment decisions. Assuming that the technology is operative when needed, AFs of heating equipment only depend on the extent that the required capacity is used throughout the year, which depends on the temporal distribution of heating needs. This study uses heating degree-days (HDD) -a common metric used to size heating equipment- as a proxy of daily heating needs. We propose a simplified method to calculate the AF of heating equipment, dividing the daily heating needs by the maximum daily heating requirement during the studied period. The AF is approximated by the average HDD divided by the maximum HDD. We compared our method with an alternative approach (Papakostas et al. 2009) and it produced very similar results. For clarity, the calculation and underlying data is made available (Astudillo 2017). HDD were calculated based on hourly temperature measurements during the period 2008-2015 (Govt. of Canada 2016a) in Montreal, the largest city in the Quebec province. A sensitivity test was conducted to assess the potential variability within the province comparing monthly HDD for the biggest cities in the province (Fig A.12). These cities have similar demand profiles, and therefore the data from Montreal is considered to be representative of the region.

Temporal distribution of demand

Most of the energy demand in the household sector is for household heating, but there is no time-disaggregated data available on its distribution through the year, compromising the temporal representativeness. In the absence of specific data, other TIMES models have inferred the distribution of demand from HDD (Hagos et al. 2017). The heating demand in the residential and commercial sectors is assumed to be linearly proportional to the seasonal HDD (i.e. heat loss is dominated by conduction). This assumption was validated with empirical observations, combining a dataset of hourly electricity consumption (Régie de l'énergie Quebec) and temperature (Govt. of Canada 2016a) for the period 2009-2015. For days requiring heating (i.e. positive HDD), electricity consumption is strongly linearly correlated with outdoor temperature (Fig. A4 in Annex A).

The second largest source of energy demand is domestic water heating, followed by lighting and the use of miscellaneous electric equipment (NRCan 2013). Hourly consumption profiles for these demands were obtained from the building simulation software Can-Quest, a Canadian adaptation of the eQuest software. The demand for these services is bimodal, with a morning and evening peak, which correspond with the time slices selected in NATEM-QUEBEC.

Heating equipment efficiency and costs

For conventional heating technologies, costs (Canadian GeoExchange Coalition 2010; EIA 2015; R. S. Means company 2015) and efficiencies (Caddy 2015; EIA 2015; EPA 2017) were revised based on North American literature. For heating technologies whose performance depend on climatic conditions, literature from Quebec was used. The efficiencies of cold-climate air source heat pumps and geothermal heat pumps are based on a study in Montreal, calibrated with experimental data from a demonstration project in Ontario (Tamasauskas et al. 2013). We tested the possibility of lower efficiencies, as field trials in other countries have found lower savings than expected, mostly attributable to poor quality installations (Staffell et al. 2012). For solar combisystems, the efficiency and costs are based on (Cheng Hin and Zmeureanu 2014). Technologies with small market shares are expected to improve due to learning effects and economies of scale. The projected improvements in efficiency and costs of heat pumps are based on forecasts from the International Renewable Energy Agency (IRENA and IEA 2013). CH_4 and N_2O emission factors for pellets and log stoves were obtained from the LCA database ecoinvent (Wernet et al. 2015). The parameters defining heating equipment are summarised in Table A1.

Energy conservation savings and costs

Changes in the building envelope of buildings could result in substantial reductions of household energy needs (Tamasauskas et al. 2013) also reducing the peak demand. According to the IEA, building envelope improvements are critical and given the long lifespan of buildings, and "it is vital that opportunities are not wasted" (IEA 2013a). Several improvements in the building envelope were evaluated in an alternative scenario, including changes in the roof, above and below ground walls and windows. The description of the conservation measures, their associated costs and energy savings are available in Table A2 (annex A). Each intervention was modelled with the software Can-Quest, using as a baseline the average characteristics (size and thermal envelope characteristics) of detached houses in Quebec as characterised in the CSDDRD database (Swan et al. 2009). The database includes more than 2880 detached houses and provides a statistically representative sample of the housing stock in Quebec. The interventions that were more cost-effective or had higher potential savings were implemented in NATEM-QUEBEC. We simulated interventions that resulted in a range of thermal resistance values above and below those proposed by the IEA for cold countries (IEA 2013b) and Quebec building code (Govt. of Québec 2017) (comparison in Table A3). The uptake of high performant building envelopes would provide evidence that building codes should be stringent. Certain constraints, such as the amount of energy potentially saved by conservation measures were imposed based on the characteristics of the housing stock and the energy savings in an average house. For the case of programmable thermostats, energy savings come from a Canadian study using an older version of the CSDDRD database (Guler et al. 2001). All the costs of upgrading building envelopes were obtained from the RSMeans database (R. S. Means company 2015). Further details on the modelling can be found in the Annex A.

The potential use of the improved thermal envelopes in newly built houses was also calculated. In newly constructed houses, the cost of the improved thermal envelope just included the cost of the extra material required with respect to the baseline envelope. The aggregated heating demand in Quebec from new houses was estimated based on the expected growth of demand plus the expected proportion of the housing stock that would be rebuilt. The latter is calculated projecting the observed changes in housing stock during the years 1990-2012 (NRCan 2013), grouped by the period of construction. This approach allows accounting the fact that older houses are comparatively less well insulated.

The CSDDRD database provides a very detailed description of the stock of detached and attached houses. Unfortunately, there is no data available on the characteristics of apartments. Therefore, the conservation measures were only made available for detached houses, which nevertheless represent 66% of residential heat demand at present.

5.2.5. Electricity sector

The following sections detail the factors that could influence the costs of supplying peak demand according to the review of the literature. The availability of renewable energy and options for electricity trade are assessed, as well as the potential emissions from hydropower, which is the main source of energy storage in the region. Other parameters such as costs and lifetime are available in the annex (Table A4).

Availability factors of renewable energy

As stated in the introduction, the temporal availability of renewable energy is important in the assessment of the cost of covering peak demand. Energy storage technologies can alleviate these mismatches between supply and demand, but in this study, we paid particular attention to intra-annual changes in supply, since long-term energy storage is not easily available. In NATEM-Quebec the availability is characterised by the AF and the contribution to peak (i.e. their availability to contribute to peak demand) (Vaillancourt et al. 2017). This section details how these parameters were estimated for hydropower, wind and solar technologies. The numerical values are summarised in Table A5.

Hydropower

Availability of hydropower is particularly difficult to evaluate because reservoir levels are commercially sensitive information and rarely available. Quebec has most of its hydropower capacity within the continental subarctic zones, and most of the hydro power is available in spring, during snowmelt. However, peak demand occurs in winter and water is stored in the existing dams throughout the year to "pass" the winter peak. Historical analysis showed that observed storage levels are considerably below the maximum storage capacity (Hydro Quebec Distribution 2014). Therefore reservoir hydropower is technically constrained at an annual level by the amount of rainfall, but not at a seasonal level. This assumption was empirically verified using monthly data of hydropower production and installed capacity data. It can be observed that hydropower is at maximum operation during winter times (Fig. A7 in annex).

In principle, run-of-river plants would have a profile of production closer to run-off of natural rivers (i.e. highest flows in spring, lowest in winter). In practice, many rivers in Quebec have reservoir power plants upstream and show an inverted regime, with considerably more run-off during winter that natural rivers (Assani et al. 2006). In the absence of disaggregated data on run-of-river production, historical daily run-off data from hydrological stations was used (Govt. of Canada 2016b). Measurement stations located close and downstream of several of the largest run-of-river power plants of Quebec were identified. The annual flow of the rivers was aggregated using a weighting average with respect to the capacity of the power plants. A representative year was estimated averaging flows during the period for which records were available (1971-1994). This representative year was then used to estimate the distribution of electricity production from run-of-river by season (Fig. A6 in Annex). For clarity the calculations are available online (Astudillo 2017). The power generated by run-of-river during winter is very close to the annual average, with the lowest generation levels in summer (when aggregated demand is the lowest). We considered that the AF of run-of-river would be at least as high as during the winter season, the period further away from spring, which is the period of maximum run-off.

Wind and solar

Hourly wind power production and solar irradiance datasets were used to estimate the AFs per time slice. The capacity factors of wind were calculated from the datasets made available by the Pan-Canadian wind integration study (General Electric International 2016). These datasets include hourly production values during the period 2008-2010 for more than 1380 potential sites in Quebec (see SM and Fig. A8 for more details). The contribution to peak is estimated based on a study of Hydro-Quebec (Hydro-Quebec Distribution 2009). The AFs for solar energy are based on the temporal distribution of solar irradiance in Montreal (Govt. of Canada 2016c) and the annual AF for Quebec (Trottier energy futures project 2016).

Limits to variable renewable energy

As mentioned in the introduction, the temporal resolution of TIMES models is not detailed enough to detect potential curtailment of highly variable renewable sources such as wind power. Power systems with large amounts of hydropower offer easier integration of wind and solar technologies, but modelling the interaction is complex (Huertas Hernando et al. 2016) and beyond the capabilities of TIMES. For this study, the penetration of wind resources is limited to 35% of the annual electricity generation based on results of a large Pan-Canadian wind generation study (General Electric International 2016). They estimated that significant curtailment could occur in Quebec at those levels unless other measures are taken, such as the reinforcement of the transmission grid to connect wind resources to centres of demand. Since NATEM-QUEBEC already includes the transmission development costs in the wind technology cost, 35% is used as an upper estimate. An additional constraint was imposed, limiting the penetration of wind power per time slice to 70% of total generation. A complementary sensitivity analysis (scenario limittoREN) assesses an additional constraint, where the sum of run-of-river, wind and solar are not allowed to exceed 50% of the annual electricity mix. The constraint is probably conservative since other studies based in the United Kingdom energy system found that 60% penetration of variable renewable energy was feasible with little cost increase (Pfenninger and Keirstead 2015).

Electricity trade

Electricity trade can be used to alleviate peak demand, but higher costs of electricity in winter and energy security reasons tend to limit the amount of imported electricity. The share of imports can also oscillate over the years, descending when new capacity is built and gradually increasing as demand catches up. We assume that energy security concerns will keep the share of imports close to current levels. The maximum imports per year and per time-slice are derived from a dataset of hourly imports during the period 2009-2015 (Fig. A9 in annex).

The analysis shows that during certain hours the share of imports in Quebec can be as high as 45%. This large percentage is explained by the existence of a long-term contract to operate the Churchill-Falls hydropower plant situated in Newfoundland & Labrador, by far the greatest source of electricity imports. Because the plant is under the control of Hydro-Quebec, imports from this region can be used to cover peak demand. It is assumed that only 5% of imports from other neighbouring regions can contribute to peak demand. The contract with Churchill-Falls operates until 2041 and guarantees an extremely low purchase price of 0.002 CAD/kWh. This price was modelled in NATEM-QUEBEC, assuming prices will converge to those of other importing regions by the end of the contract.

As mentioned in section 5.1.2, emission embedded in imports can have a significant role in GW mitigation scenarios, and their omission could result in CO_2 "leaking". Except for imports from Churchill-Falls, it is assumed that electricity imports will come from combined cycle gas power plants. This assumption is consistent with default emission factors applied in regions under cap & trade policies such as California (Bushnell et al. 2014) which is part of the same emission market as Quebec. Consistent with the rules of the CO_2 market in Quebec, electricity exports do not receive emission credits.

Emissions from hydropower

To account for the emissions from new reservoir hydropower we use the results from a unique experiment of its kind, which was done in Quebec. During the period 2003-2009 CO_2 and CH_4 emissions were quantified before and after the creation of the Eastmain reservoir (Teodoru et al. 2012). The survey observed how CO_2 and CH_4 emissions peaked the first years and then declined steadily. Extrapolations of the empirical trends over the lifetime of the reservoir were used to estimate the emissions of 62 t CO_{2eq} GWh-1, around seven times lower than a natural gas combined cycle power plant (Teodoru et al. 2012). No emissions were considered for existing reservoirs as the additional CO_2 emissions only occur during the first years after the creation of the reservoir and most of the existing ones were built decades ago. Furthermore, emissions seem not to be affected by its operation.

5.2.6. Scenarios

Several scenarios were developed around the main mitigation scenario (GHG50), in order to evaluate the different assumptions of the model (Table 5.1). All the scenarios include a reduction on GHGe inspired in current policies (37.5% reduction and 50% reduction in GHGe emissions by

2030 and 2050 respectively with 1990 as a baseline) except for the BAU scenario. The other scenarios explore the implications of changing key assumptions of the GHG50: the addition of conservation measures (section 5.2.4), emissions from reservoir hydropower (section 5.2.5), limits variable renewable energy (section 5.5.2), the effect of densification of urban developments (section 5.2.3), the relaxation of constraints to the electrification of other sectors (annex A) and the possibility of heat pumps being less efficient (Staffell et al. 2012).

Table 5.1: Characteristics of the scenarios

Scenario	Difference with GHG50
BAU	No constraints on GHGe
Conservation	Conservation measures available (section 5.2.4)
noGHGhyd	No emissions from new hydro reservoirs (section 5.2.5)
limttoREN	Additional constraints on the development of ren. Energy (section 5.2.5)
Impr.urban	Changes in the demand for energy services (section 5.2.3)
HP_eff	Heat-pumps are 30% less efficient (section 5.2.4)
NoINDconst	No constraints to the electrification of industrial energy demand (annex A)

5.3. Results

The following sections describe the results of the modelling. Section 5.3.1 and 5.3.2 describe the cost-optimal heating technologies in the residential sector and the potential effect of conservation measures. Section 5.3.3 outlines the changes in electricity peak demand and the contribution by sector and section 5.3.4, which would be the cost-optimal technologies to cover the increasing demands of electricity. Finally, section 5.3.5 compares the system costs of the different scenarios. Many scenarios presented the same trends and to avoid repetition just the more relevant are shown in the results section. Additional results can be found in the Annex A.

5.3.1. Household heating technologies

Fig. 5.1 represents the cost-optimal technologies in the GHG50 scenario in the household sector. After some supply-demand adjustments and technology developments, cold climate air based heat pumps gradually become the cost-optimal solution for household heating. Electrification of the heat supply takes place steadily, with gas and biomass being initially part of the solution but eventually disappearing. Other low-carbon technologies such as solar thermal are too expensive to be part of the optimal solution.

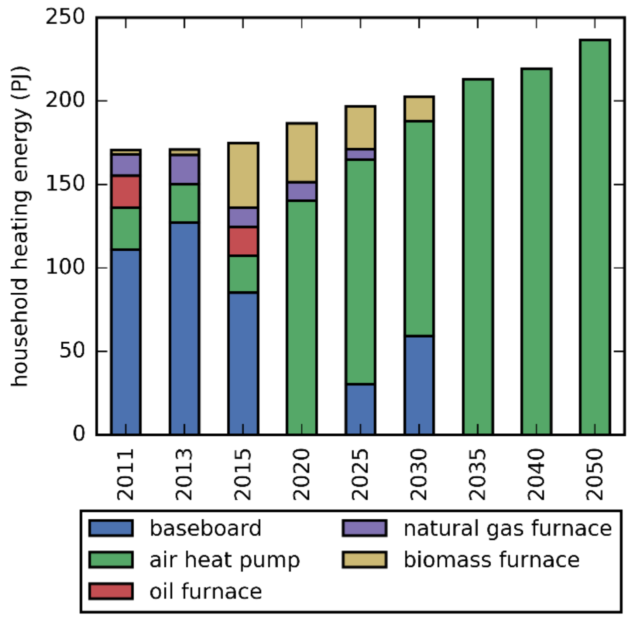

Figure 5.1: cost-optimal technology mix of household heating technologies in Quebec (2011-2050) (GHG50 scenario). (Aggregated demand of the four housing types)

There is a temporary rise in heat supplied by baseboards in 2030, due to a lower price of electricity during that period. This increase is nonetheless a transient phenomenon, and air based heat pumps gradually become the preferred technology. The rest of the scenarios with GHG constraints showed a similar trend, with air cold-climate air heat pumps gradually taking over the heating supply of cost-optimising households. The most remarkable deviations from the observed trend were found in the sensitivity scenarios. If the constraints of electrification for other sectors are eliminated, natural gas furnaces have a more relevant role (Fig. A11 in SM). If efficiencies of heat pumps are lowered by 30% the uptake of heat-pumps is much slower but eventually become the cost-minimising option (Fig. A11 in SM).

The other main changes in households include the uptake of more efficient electric appliances and switch from incandescent lamps to solid-state lighting.

6.3.2. Conservation measures

In the scenario considering conservation measures, only two of the considered measures are cost-effective in existing buildings, programmable thermostats and improvements in the envelope of the basement.

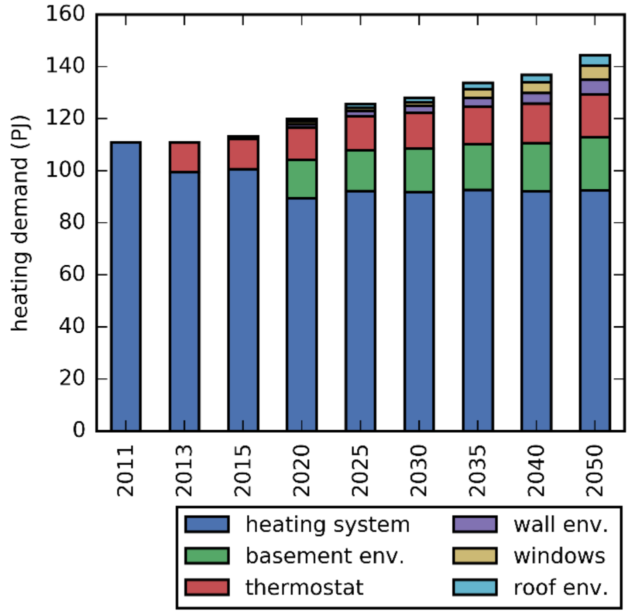

Figure 5.2: cost-optimal technology mix of heat supply in detached households in Quebec (2011-2050) (conservation scenario)

For new dwellings, the best-insulated envelopes have a full uptake in most of the cases (Table A2), offsetting the projected increases in heating demand (Fig. 5.2). By 2050, 34% of the primary demand for household heating is "supplied" by conservation measures.

Most of the reductions in GHGe caused by conservation measures occurred in the residential sector, with around -2515 kt CO_{2eq} less cumulative emissions compared with the GHG50 scenario. Other sectors such as industry raised the cumulative emissions (+117 kt CO_{2eq}) with respect to the GHG50 scenario because under the same emission budget it is cheaper to abate emissions in the residential sector. Air tightness was found to be a critical parameter in the simulations. The same conservation measures are about 30%-50% less efficient if they are not associated with an improvement in air-tightness.

5.3.3. Contribution to peak demand

The scenarios with a GHGe constraint have around 30% higher electricity peak demand in 2050 than the BAU scenario (Fig 5.3). The increase of peak demand is caused by the electrification of services provided by fossil fuels. The technological options available in the residential sector allow to considerably reduce its contribution to electricity peak demand, from 50% in 2011 to 25% in 2050 (GHG50 scenario).

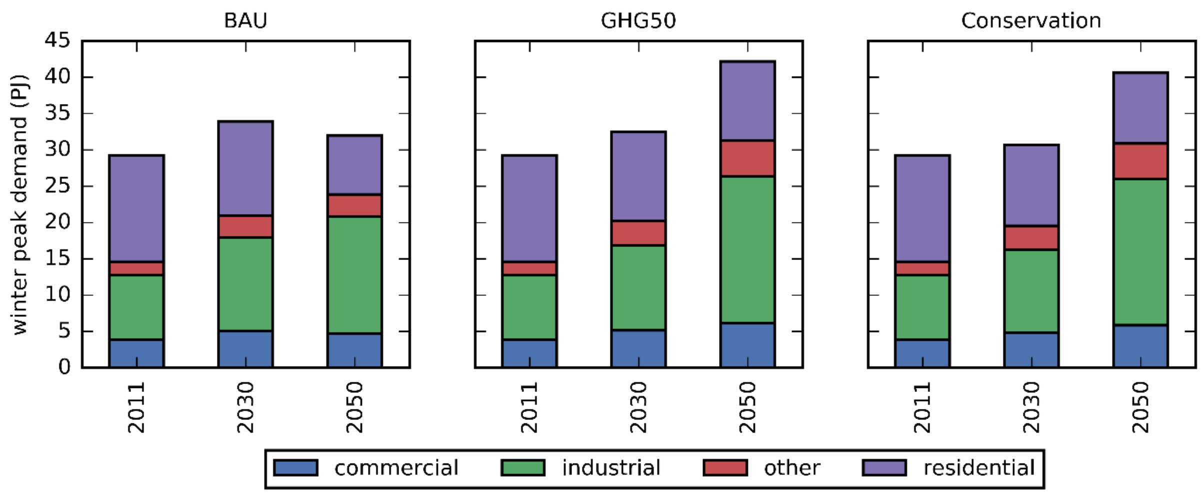

Figure 5.3: Cost-optimal electricity peak demand in Quebec, by sector (winters 2011, 2030 and 2050) for the BAU, GHG50 and conservation scenario. Peak demand is represented by the morning peak, very similar results were found for the evening peak.

The conservation measures on detached households reduce by 10% the aggregated winter peak demand with respect to the GHG50 scenario. Further savings are possible if the conservation measures were extended to apartments and attached houses.

5.3.4. Electricity supply

Fig. 5.4 displays the electricity production per year and production technology for all scenarios. In the BAU scenario, reservoir hydropower supplies the increase in electricity demand. The same trend is observed in the scenario were emissions from reservoirs are neglected, but a cap on GHG is imposed (scenario noGHGhyd). In the rest of the scenarios, the rise in demand is covered by an increase in run-of-river and wind power plants. The scenario with a limit on cumulative production from variable renewable energy, additional imports from Newfoundland and Labrador are used to meet the demand. In the rest of the scenarios, the imports from Newfoundland and Labrador are notably reduced when the long-term contract to operate the Churchill-Falls power plant expires, and price of imports converges to those of other neighbouring regions. In all the scenarios imports from regions powered by fossil fuels decrease to nearly zero, partially motivated by the "embedded" emissions in electricity imports. Fig. 5.4 also shows how GHGe reduction implies higher electricity generation with respect to the BAU scenario, where no constraints on GHGe is imposed.

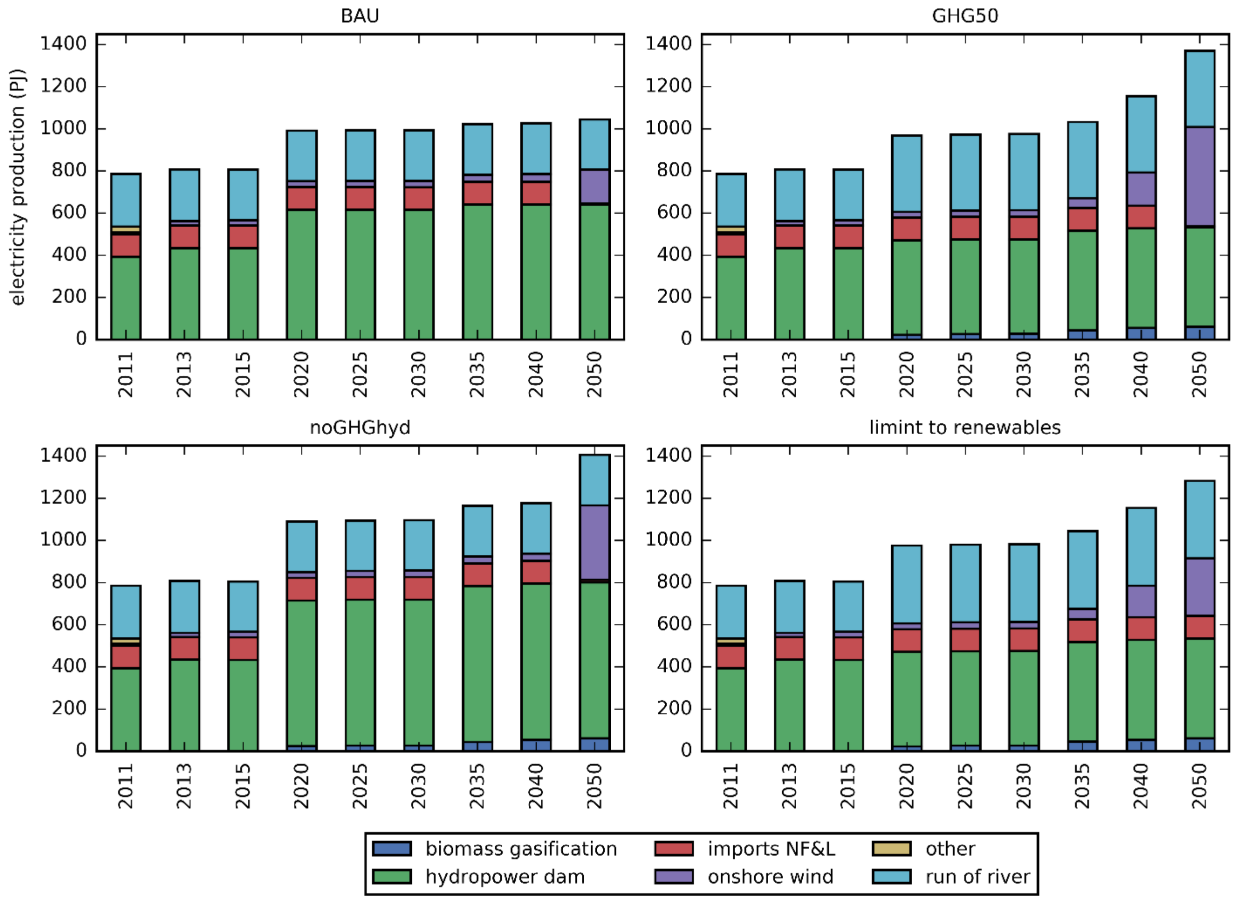

Figure 5.4: cost-optimal electricity supply mix in Quebec (2011-2050) by scenario.

5.3.5. Cost comparison

Comparing the costs of covering energy needs with respect to the scenario without GW constraints (BAU) allows estimating the cost of GW mitigation efforts. Reducing by 50% the GHG emissions for 2050 would result in nearly a 20% increase in the cost for most of the scenarios (Fig. 5.5). The scenario that introduces the possibility to include conservation measures (e.g. change building evenlopes) has 14% lower mitigation costs than the reference mitigation scenario (GHG50). (Fig. 5.5). If households continue to rely on electric resistive heating systems (HP less eff scenario), the transition would be 11% more costly.

A better urban design, with a switch in housing and transportation modes, can meet the same mitigation objectives at a much lower cost, similar to the expenses of the scenario without emissions constraints.

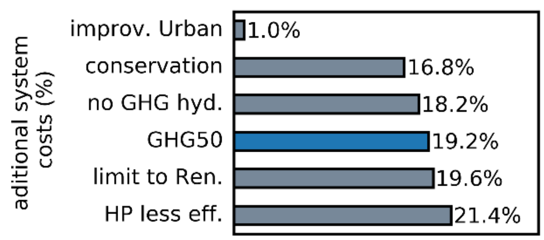

Figure 5.5: additional system costs of energy supply in Quebec relative to the BAU scenario.

In scenarios with GHGe constraints, investment costs are dominated by electrification of cars and electricity production. The scenario Impr.Urban reduces the need for road transport, subsequently reducing its costs. The conservation measures reduce the system costs by reducing the needs for electricity production.

5.4. Discussion

Energy system models are necessarily a simple version of reality, and results have to be interpreted with caution. Like other scholars, we focus on insights (DeCarolis et al. 2017) analysing the results in the light of the limitations of the model. In the following sections, we attempt to clarify result's implications for the transition to low-carbon societies as well as for the models and data that underpin this transition.

Results are compared with projections of other models to assess their coherence, and contrasted with historical trends to identify potential barriers to a low-carbon transition. The results are also contextualised taking into account the limitations of the model, in particular with regard to human behaviour.

5.4.1. Residential sector

Cost-optimal technological choices

Results in the residential sector are coherent with those from other optimisation models that find heat pumps among the preferred technologies to transition to low-carbon households (Dodds 2014; Cayla and Maizi 2015; Deane et al. 2015). The uptake of heat pumps is cost efficient despite their lower efficiency in severe continental winters such as the ones encountered in Quebec. Even if heat pumps were 30% less efficient, they eventually become the cost-optimal technology (Fig. A11 in SM). The results underline the importance of adapting efficiency and AF to regional climates. Availability factors are rarely discussed in the literature, and efficiency values range considerably (IEA 2013a). Thus, using generic values can result in misleading recommendations.

Results should be interpreted within the limitations of the model. For example, NATEM-Quebec does not differentiate different regions within the province, and winters will be colder in some smaller cities in the north of Quebec. In colder areas, heat pumps will be less efficient, and full uptake of this technology may not be feasible. Nonetheless, most of the population is concentrated in the southern part of the province, and the main cities have similar heating demand profiles (Fig.

A12); thus, the simplification is not likely to have a significant impact on the observed trends. Some studies underline the barriers that can emerge for geothermal heat pumps, whose efficiencies depend on uncertain geological characteristics (Bleicher and Gross 2016) and where space can be a limiting factor (Petrovic and Karlsson 2016). However, to our knowledge, the main constraint for air based heat pumps is the minimum operation temperature, which has been considered.

Other non-considered factors may further favour heat pumps. Economies of scale, which have not been considered in this study, would play in favour of heat pumps, as larger equipments have higher efficiencies (IRENA and IEA 2013) at comparatively lower costs (Canada Geoexchange coalition 2010; Staffell et al. 2012). Geothermal heat pumps can also act as thermal storage, providing further load-shifting capabilities that were not considered here. Studies including the effect of GW in similar regions suggest heat demand will decrease and cooling demand will rise (Seljom et al. 2011). Therefore, GW will probably favour heat pumps, which provide heating and cooling and whose efficiency rises with temperature. Furthermore, preliminary analyses based on LCA methods, suggest that the implementation of heat pumps will also consistently reduce environmental burden in other areas of concern, such as human health, ecosystem quality and resource depletion, while other technologies present clear tradeoffs (Astudillo et al. 2015a). This reduction is possible despite the fact that heat pumps use refrigerants, which have global warming potentials several orders of magnitude larger than CO_2.

Fossil fuel technologies such as gas furnaces play a role in cost-optimal mitigation pathways but gradually disappear as higher GHGe reductions are required. The transition role is more prominent in the NoINDconst scenario (Fig. A11), where gas furnaces dominate the market for an intermediate period. The more alternative uses we consider for electricity, the less sense it makes to use resistive heating systems. This trend is consistent with the scenarios developed by the IEA and their recommendation to avoid electric resistive heating as main heating system (IEA 2013a). Furthermore, gas furnaces could substitute baseboard heating and use the electricity savings to offset gas-powered electricity production in neighbouring jurisdictions. This option could be a national mitigation strategy as far as Quebec exports offset fossil-fuelled power plants. For this to happen, electricity exports would need to be credited for emissions abated elsewhere, which is not currently the case. In that sense, current CO_2 market policies are constraining trade-based mitigation strategies.

The uptake in of thermal envelopes with thermal resistance values above those of current building codes in new dwellings is an indication that Quebec codes should be more stringent (Tables A2 and A3). The use of a long-term model considering mitigation costs, together with building simulation, permits to evaluate current building codes from a different perspective, considering future CO_{2eq} abatement costs. Other studies have found very high CO_{2eq} abatement costs in the long-term (Vaillancourt et al. 2017). Given the low refurbishment rate of buildings (1% for OECD countries (IEA 2013a)), it is necessary to consider the future high mitigation costs in the assessment of adequate housing standards. While the results are specific to Quebec, the method can be replicated to evaluate other building codes. These results are also consistent with the GW mitigation scenarios of the IEA, which highlight the importance of building envelopes as a GW mitigation strategy (IEA 2013b). Despite the fact that changing the building envelope is often not cost-efficient in an existing average home, the big variability found in thermal resistance of the housing stock suggests that it could be cost-efficient for the older houses, which are typically poorly insulated (Fig. A1 in annex). Hence, further disaggregation of the residential sector could be useful.

Conservation measures could also be extended to apartments and attached houses, but there is currently a lack of information on the building envelope characteristics of apartments. Finally, the energy savings from thermostats highlight the possibilities of mitigation of simple behavioural changes.

Simulations also highlighted the importance of air-infiltrations on the achievement of energy efficient homes in Quebec. Energy savings were much lower if upgrades did not also improve air-tightness. Air-tightness is likely to be relevant in other cold regions and energy system models assessing conservation measures in cold climates should consider its influence. Not surprisingly, a tight control of air flows is at the core of reference standards such as passivhous (IEA 2013b). The IEA states that air-sealing alone can reduce the need for heating by 20-30% (IEA 2013b). In Quebec, measures of air-tightness in the existing housing stock show average values of 6.19 and 7.97 ACH50 for detached and attached houses respectively. Average air-tightness indicators are well above the recommended values of 1.5 ACH50 of the (non-compulsory) Canadian standard R-2000 or the 0.6 ACH50 of the passivhaus standard (IEA 2013b) (Fig. A2 in SM).

Reducing the gap between cost-optimal and observed behaviour

All scenarios show substantial changes in the residential sector, with a shift to heat pumps and solid-state lighting as well as improvements in the building envelope for new construction. Overall, these changes reduce peak demand and contribute to the reduction of the costs of GW mitigation. However, many of these changes will likely not take place unless policies are implemented. Effective mitigation would require a shift from the past policies in the region, where energy efficiency objectives have repeatedly been lowered or abandoned (Langlois-bertrand et al. 2015). It also requires a shift in purchasing habits, for example, Quebec households still rely on inefficient incandescent bulbs for lighting (NRCan 2011), while much more efficient alternatives are available. The global residential sector is subject to multiple market barriers, and Quebec is no exception. Residential electricity price is regulated (and effectively subsidised) and considerably below marginal costs, which biases the investment towards production and against energy efficiency. Moreover, tariffs are mostly based on energy and do not reflect the costs of peak demand (Pineau and Langlois-Bertrand 2016). Previous studies found that economic factors are the main determinants of retrofit decisions in Canadian households (Gamtessa 2013) and that at current electricity prices many retrofits are not feasible (Guler et al. 2001), which calls for electricity tariffs that better reflects the costs.

Previous research found that split incentives problems affect energy efficiency behaviour in Canadian households (Maruejols and Young 2011; Burak Gunay et al. 2014). Stringent building codes are cost-effective and could be a way around the split incentive problem.

We stress the importance of differentiating between technical constraints and behavioural constraints in optimisation models. Including both conflates what is considered desirable under the economic welfare paradigm (i.e. cost-minimising decisions) with “realistic decisions”, complicating the interpretation of the results. Optimisation models are by design well suited to study cost-optimal behaviour, and running scenarios just with technical constraints facilitates the identification of areas where market barriers are more entrenched, and interventions to accelerate the uptake of low-carbon practices may be needed.

The potential for denser urban areas

The scenario Impr.Urban envisions cities with denser urban planning, relatively smaller houses and higher use of public transport. Results suggest that urban planning could be a very efficient strategy to mitigate the costs of the needed energy transition.

The average dwelling surface rose by 54% in Quebec in the period 1990-2012 (NRCan 2013), much faster than the 16% population growth. Most of the growth occurred in the single detached houses, which by configuration have the highest exterior area to living area ratio and therefore require more heating. Consequently, reversing the observed trend lowers the need for heating and heating peak demand. Nonetheless, most of the economic savings in the improved urban scenario arose from transport savings, as electric cars are still an expensive substitution alternative. Changes to denser urban areas, with more compact households also reduce transport needs, reducing the costs of abating transport emissions. A palpable example can be seen in the city of Toronto, where a study accounting transport and household energy consumption found that low-density suburban developments are 2-2.5 more energy and GHGe intensive per capita than denser developments (Norman et al. 2006). Other regions where urban sprawl is common (e.g. North America) may also find densification as a suitable mitigation strategy. More generally, results underscore the importance of considering potential changes in demand for energy services as well as doing sensitivity analyses on the way services are segmented. For instance, housing needs can be fulfilled with different housing types, and not considering the possibility of changes in demand ignores alternative, potentially interesting mitigation pathways.

5.4.2. Electricity supply

Contribution of renewable energy sources

Quebec has a large reservoir capacity that explains why the electricity expansion can be done with less predictable renewable energy sources. It also benefits from long-term contracts (Churchill-Falls reservoir) that help to supply peak demand. These two factors mitigate the cost of the increasing peak demand. Other regions with less storage capacity or beneficial trade agreements, may experience much higher abatement costs during their transition to low carbon electricity supply. Results evince the importance of considering electricity trade when assessing GW mitigation strategies.

This study does not include the influence of GW in the energy system, which is likely to affect renewable energy resources. On the one hand, GW will probably increase hydropower potential (Minville et al. 2010; Seljom et al. 2011), on the other hand, efficiency and reliability of plants may be compromised by a rise of unproductive spills (Minville et al. 2010). We left the influence of GW out of the scope, as it is an extensive study on its own.

Hydropower emissions

One of the remarks of the study is that emissions from reservoirs should be considered in the assessment of mitigation scenarios. In the scenarios where these emissions are considered, reservoirs were substituted by run-of-river plants and wind power plants. This study has the advantage of using first-hand experimental results done in the region, but other studies could rely on inferential results such as those proposed by Scherer and Pfister (2016). When using results from statistically inferred models, uncertainties need to be considered carefully, as explanatory variables are not able to explain the variability found in the different reservoirs (Barros et al. 2011; de Faria et al. 2015). Hydropower is still the main source of renewable electricity worldwide and continues to dominate renewable capacity additions (IEA 2012). Without a careful assessment of reservoir emissions and how to mitigate them, these huge investments could backfire as a GW mitigation strategy. The risk is particularly notorious for hydro projects conducted in the Amazon basin, were higher GHGe are expected (Barros et al. 2011; de Faria et al. 2015).

Although water availability is not an immediate concern in Quebec, an experimental assessment of the net water footprint of the Eastmain reservoir demonstrated that the contribution to water scarcity of reservoirs is much lower that previously stated (Strachan et al. 2016). The underlying reason is that pre-flooded landscapes already consume considerable amounts of water. The contribution to water scarcity is regionally dependent, and it could still be a constraint to the use of reservoir hydropower to provide peak demand in arid regions.

5.4.3. Limitations and perspectives

This study explores long-term GW mitigation strategies in Quebec using a multisector model. The focus is in the residential sector and electricity supply, key determinants of peak demand costs. The multi-sector assessment allows identifying inter-sectoral mitigation opportunities (e.g., electricity savings in households used to electrify transportation) which would not be identified by single-sector models. Nonetheless, it is clear that efforts in the residential sector alone are not sufficient to reach Quebec's GW mitigation targets and other sectors should be considered in more detail. A more disaggregated characterization of the energy use in the industrial sector would be needed for further assessments.

Cost-optimal technological choices for heating equipment and electricity production in this study are more relevant for regions with similar climate and hydropower capabilities, such as British Columbia or Norway, but not directly translatable to other regions with CO_2 intensive electricity mixes. However, results from Quebec provide insights of what other regions may need to do in the future. Moreover, the methodological approaches and recommendations can be used in other TIMES models.

Having a technological, geographical and temporal representative data in long-term mitigation scenarios requires large amounts of information that are not always publicly available. For instance, there is no publicly available data on the characteristics of apartments, the temporal distribution of heating demand or the capacity factors of state-owned power plants. The lack of primary data can sometimes by mitigated with proxy data available through public institutions or research initiatives. This article has used several of these sources, including hourly electricity consumption and trade, temperature, runoff, solar irradiance, wind production and envelope characteristics of buildings. The data sources have allowed us to infer key parameters of the energy system, providing robustness to the results. Some resources are better documented than others (e.g. wind vs. Run-of-river) and different methods were used to estimate the AF, compromising data quality to some extent. In the absence of official data, a method is proposed to calculate AF of heating equipment based on historical HDD. This method can be used to obtain geographically representative parameters for other TIMES models. Further studies can quantify the impact of the uncertainty related to data quality (epistemic uncertainty) using the pedigree method, as proposed in ref (DeCarolis et al. 2017). The epistemic uncertainty can be combined with the variability resulting from temporal segmentation using stochastic versions of TIMES. We thus encourage that open-data initiatives continue to be developed, as planning based on informed decision vastly compensate the costs of collecting and maintaining the datasets.

Finally, the scope of the study can be enhanced incorporating more information from LCA databases. This study already integrates some elements of LCA thinking, such as emissions from reservoir creation or electricity imports. However, more formal and comprehensive integrations are possible (Astudillo et al. 2017a), quantifying impact in other areas of concern such as human health, ecosystem quality or resource depletion.

5.5 Conclusions

The use of a long-term energy system model together with building simulations, calibrated in the province of Quebec led to the identification of several features of the transition to low-carbon societies. On the demand side, the GW mitigation scenarios raised the peak demand of electricity, increasing the costs of fulfilling energy needs. The rise in peak demand and its costs in Quebec can be effectively mitigated by interventions in the residential sector, switching to more efficient heating systems such as heat pumps, using energy-efficient appliances and installing better building envelopes. With some exceptions, the studied improvements on building envelopes are not cost-effective for the existing average houses, but have a strong uptake in new buildings, suggesting building codes should be stringent. The results stressed the utility of using a long-term multisector model to assess GW mitigation strategies of the residential sector, and the importance of considering the characteristics of the existing housing stock when assessing conservation measures. Moreover, technological parameters such as AF and efficiency can be severely dependent on regional temperatures, and its effects should be considered. In the absence of experimental data, we propose a method to calculate AF of heating equipment using temperature data. This method can easily be implemented in other models, improving the geographical representativeness of the model.

Additionally, the scenario considering urban densification and modal changes in urban transport reduced by an order of magnitude the GW mitigation costs, ilustrating the importance of urban planning. The results also underscore the importance of considering potential substitution effects between energy services that provide a similar function (e.g. large cars – light trucks). The substitutability of energy services is de facto determined in energy models with the segmentation of demand, and the segmentation will affect the identification of mitigation opportunities. Therefore, modellers should carefully consider the constraints that particular segmentations of demand entail.

The analysis of the optimal capacity expansions of electricity supply is dependent on the regional options for renewable energy sources. In regions such as Quebec, endowed with large hydro storage capabilities, run-of-river power plants and wind generation are preferable to reservoir hydropower, which causes non-negligible emissions during its creation. Despite being comparatively low in this case, emissions from hydropower should be considered when assessing GW mitigation options. The effects upstream reservoirs in run-of-river power plants operation should also be taken into account, as it can substantially differ from runoff patterns of unmanaged rivers.

The study of peak demand requires disaggregated intra-annual data on demand and renewable production. In the many instances where this data is not available, this study exemplifies several cases where proxy variables can be used to model the temporal distribution of supply and demand. Furthermore, soft linking energy system models with results from other approaches such as building simulation software permits to leverage the power of different model paradigms and available data.

Finally, the differences between observed behaviour results from the model need to consider that the results represent technically plausible cost-optimal pathways, not forecasts. Quebec is subject to several market barriers (subsidised consumption, split-incentives, etc.) And these factors could slow the technological transformation to a low carbon society. Potential policy measures to unlock the energy efficiency potential include stringent building codes and a revision of subsidies for energy household consumption.

CHAPITRE 6: LIFE-CYCLE IMPACTS OF A CLIMATE CHANGE MITIGATION STRATEGY

Avant-propos

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Titre en français : Impacts d'une décarbonisation profonde du système énergétique sur la santé humaine et les écosystèmes

Contribution au document : adaptation du modèle NATEM pour répondre aux questions de recherche.

Résumé

Les stratégies d'atténuation du réchauffement climatique pourraient être mieux acceptées si nous avions une connaissance des effets potentiels sur l'environnement et la santé humaine. Pour analyser ces effets, une méthodologie permettant de lier un modèle d'optimisation des systèmes énergétiques largement utilisé et l'analyse du cycle de vie a été développée. La méthode est utilisée pour évaluer les effets potentiels du déploiement de technologies à faibles émissions de carbone afin de réduire les émissions de combustion au Québec (Canada). Le déploiement de technologies à faible émission de carbone peut réduire l'impact sur la santé humaine et la qualité de l'écosystème, principalement en raison de la réduction du réchauffement planétaire, de la rareté de l'eau et de la contamination par les métaux. Dans une perspective cycle de vie, on constate une réduction supplémentaire de 23% des émissions de CO_{2eq}. Le déploiement de technologies à faibles émissions de carbone augmenterait les coûts des services énergétiques de 20%. La méthode proposée simplifie considérablement l'intégration des modèles, car même dans les modèles très

riches en données, seulement quelques technologies dominent les changements des émissions de CO_{2eq}.

Abstract

Global warming mitigation strategies could be better accepted with a comprehensive understanding of their potential effects on the environment and human health. To analyse these effects, a methodology to link a widely used energy system model with life cycle assessment was developed for this study. The method is used to assess the potential effects of deploying low-carbon technologies to reduce combustion emissions in the province of Quebec (Canada). The deployment of low-carbon technologies can reduce the impact on human health and ecosystem quality, mainly because of lower global warming, water scarcity, and metal contamination impacts. With the life-cycle perspective, 23% additional reductions of CO_{2eq} emissions is found. The deployment of low carbon technology would raise energy services' costs by 20%. The proposed soft-linking method simplifies the analysis substantially, since, even in technology-rich models, a few technologies drive changes in CO_{2eq} emissions.

6.1 The need for integrated approaches

Global challenges such as environmental degradation and human wellbeing are increasingly pressing and interconnected (Liu et al. 2018). Technology-rich bottom-up energy system optimisation models (ESOM) are frequently used to quantify the possible effect of sustainable development strategies and identify cost-optimal global warming (GW) mitigation pathways (Pfenninger et al. 2014; Pauliuk et al. 2017). ESOMs, even when expanded into Integrated Assessment Models (IAMs) have a relatively narrow account of other stressors and their impact on human health or ecosystems (Rauner and Budzinski 2017; Arvesen et al. 2018; McDowall et al. 2018). Bottom-up ESOMs contain detailed representations of the energy system, modelled as a set of technologies interconnected by energy commodities. Some technologies have emissions associated with their operation, such as CO_2, CH_4 or N_2O (Glynn et al. 2015), but typically only a few. For instance, the IAMs used in the IPCC fifth assessment report do not include more than thirteen substances (Krey et al. 2014). ESOMs concentrate on 'direct' emissions, that is, operating emissions of technologies (e.g. tailpipe emissions in cars) but 'indirect' emissions are rarely accounted. Indirect emissions include those associated with the provision of inputs required to operate a process, (e.g. car manufacturing and dismantling or emissions from fuel production).

Multiple and often conflicting human needs need interdisciplinary methods to address them (Liu et al. 2018). Soft-linking ESOM with life cycle assessment (LCA) has been highlighted as a promising approach to overcome the limitations of ESOM (Creutzig et al. 2012; Astudillo et al. 2017a; Pauliuk et al. 2017). LCA is a method to quantify the impact of goods and services from "cradle to grave" (Hellweg and Milà i Canals 2014) and is widely used at product level. LCA databases document thousands of pollutants associated with processes and quantify their impact on human health and the environment considering multiple cause-effect pathways. These indicators are potentially more meaningful for policy design and allow to compare the relevance of different cause-effect pathways. Both bottom-up ESOM and LCA have a similar level of technological resolution, facilitating the alignment of their ontological description. The use of ESOM can improve the quality of the assessment identifying market effects and their consequences, as well as providing representative data for prospective assessments (Astudillo et al. 2017a).

6.2 Present state of ESOM and LCA integration

Recent experiences of soft-linking ESOMs and LCA suggest that wide-scale introduction of low-carbon electricity can reduce a range of pollutants such as greenhouse gas (GHG) or particulate matter (PM) (Hertwich et al. 2015) which can result in strong human health benefits (Gibon et al. 2017). However, analyses have been mostly restricted to electricity generation (section literature review on supplementary information). The methodological developments have focused on how to integrate scenario data on LCA databases without causing double-counting (Hertwich et al. 2015; Volkart et al. 2018) and how to derive LCA coefficients to be used in IAM´s or use IAM's results on LCA (Arvesen et al. 2018; Mendoza Beltran et al. 2018). Despite the advances, methodological challenges to integrating both methods are prevalent (Astudillo et al. 2018).

Integrating ESOM and LCA requires linking equivalent processes between the two models, but 'mapping' these equivalences can be a colossal task with technology-rich models, particularly if we want to go beyond the electricity sector. ESOMs like TIAM (TIMES IAM) (Glynn et al. 2015) have more than 4000 technologies defined. Finding, adapting or creating suitable LCA descriptions of all technologies is not viable. ESOMs are also continuously updated, requiring approaches that can be quickly adapted. Moreover, most of the LCA databases describe existing technologies, and harmonisation with ESOMs parameters is needed to be representative of future value-chains (Astudillo et al. 2017a). To date, parameter harmonisation has been limited to electricity generation technologies (Mendoza Beltran et al. 2018). Finally, methods to model fuel switching (e.g. fuel blends with an increasing proportion of biofuels) have not yet been described in the literature (Supplementary information section literature review).

6.3 Goal and scope

This study aims to analyse the decarbonisation of the energy system from a life-cycle perspective. To do so we formulate a procedure to soft-link LCA methods with an ESOM of the TIMES framework, possibly the most widely used ESOM (Pfenninger et al. 2014). This study does not attempt to integrate LCA indicators in a ESOM, as this would require a one-to-one mapping of all the activities (Astudillo et al. 2018). Instead we create a "LCA image" of the energy system, addressing remaining issues of parameter consistency, fuel-switching and incomplete mapping. The procedure is used to analyse the potential consequences of reducing by 70% the CO_{2eq} emissions from combustion processes in the province of Quebec (Canada) with respect to 1990 levels. The objective would mean average energy-related emissions of 1.77 tonnes CO_2 per capita, somewhat higher than the 0.48 tonnes proposed to achieve the 1.5°C target by recent studies (Grubler et al. 2018).

The function of the system under study is to provide energy services to the province of Quebec for the period 2011-2050. On aggregate these demands represent the energy needs as quantified by the official statistics, the base of the Canadian inventory of GHG (Environment Canada 2017). The consequences of the GHG restrictions are evaluated from the differences between a business as usual scenario without GHG constraints and a counterfactual scenario with them. The results shed light on whether the deployment of low-carbon technologies has co-benefits or additional CO_{2eq} emission reductions. The model also provides insights about the potential costs of the energy transition and their nature.

Results of the optimisation model represent the most cost-efficient combination of technological changes that deliver the exogenously defined energy services while respecting GW mitigation targets. Future choices may well differ from cost-optimal ones, particularly final demand sectors (DeCarolis et al. 2017). The same energy services can also be satisfied with a different segmentation of demand (e.g. modal transport changes) (Astudillo et al. 2017b). Thus, results should be interpreted as technological opportunities to transform the energy system given certain final energy demands.

6.4 Potential consequences of GW mitigation

6.4.1 Global warming emissions

Reducing combustion emissions has the potential to bring additional CO_{2eq} emissions reductions across the value chain. In the case under study, 81% are 'direct' (i.e. operation) emissions the rest being 'indirect' supply chain emissions. Hence ESOM's may miss an important part of the picture of GHG emissions reductions. Most of the GW reductions arise from changes in road passenger and freight transport, with increased use of electrified powertrains and second-generation biofuels (Fig. B5 and Fig. B10 in supplementary material). In 2050 plug-in and battery powertrains dominate passenger transport, while hybrid ones partially powered by biofuels are used in the medium-term. In the heavy-freight sector, electric road systems (CAT-ERS) are deployed up to the maximum estimated capacity in the long-term (Fig. B5). The International Energy Agency estimates CAT-ERS can compete in price with internal combustion engine powertrains in the long-term (IEA 2017), which is in line with these results. Quebec has low-carbon electricity at relatively low cost, which also favours electrified systems. GW emissions are dominated by CO_2 from fossil combustion.

Around 83 % of CO_{2eq} emissions reductions take place within Quebec, but there is a notable increase in CO_{2eq} emissions in the US states neighbouring Quebec, due to decreased electricity exports. The carbon market between Quebec and California does not credit emissions reductions from electricity exports, creating an incentive for self-reliance (Astudillo et al. 2017b). This incentive explains the decrease in exports and subsequent rise of emissions in US from gas-powered power plants. Mitigation policies would be more economically efficient with inter-regional cooperation, and indeed policy agendas based on self-reliance can conflict with GW mitigation efforts (Jewell et al. 2016).

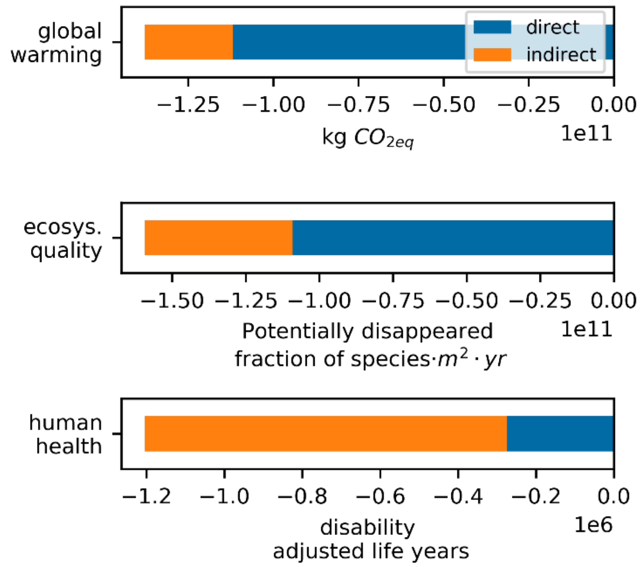

Figure 6.1 Potential effects of GW mitigation on global warming emissions, ecosystem quality and human health (direct and 'indirect' (supply chain) components).

6.4.2 Human health and ecosystem quality

Not all the cause-effect pathways contribute to reductions in human health and ecosystem burden (Fig. 6.2). Long-term (>100 years) effects dominate the potential benefits on human health, mostly through reduced GW and reduced exposure to carcinogenic substances (Chromium VI). The scenarios show a reduction in electricity production around the globe, with concomitant reductions in water scarcity from cooling systems. Water consumption from electricity production facilities is likely to be exacerbated by the ongoing substitution of once-through flow cooling systems by evaporative systems (Kyle et al. 2013). However, water consumption could be mitigated with the introduction of dry-cooling systems, that have slightly higher costs (Kyle et al. 2013).

Ecosystem quality impacts are dominated by freshwater ecotoxicity, global warming reductions and land transformation effects (Fig. 6.2). GW mitigation increases low-carbon electricity demand and in Quebec this demand is partially covered by increasing amounts of hydropower generation. More hydropower means more loss of natural habitat through land transformation; however, the net effects of the GW mitigation policy are positive. Freshwater ecotoxicity improvements are due to reduced metal contamination in waste handling processes (Fig. B10).

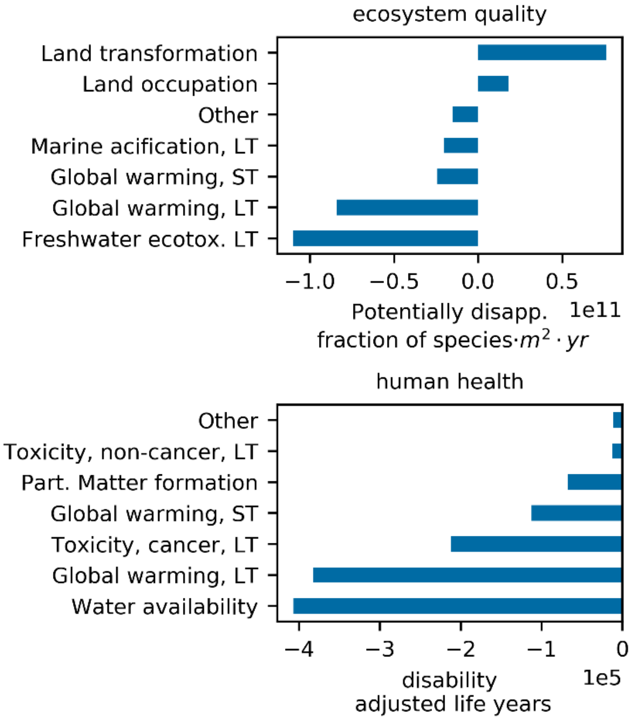

Figure 6.2 Ecosystem quality and human health impacts disaggregated by cause-effect pathway. LT: long-term, ST: short-term

6.4.3 Transition costs

Despite the importance of costs, studies of energy transitions rarely talk about them (McCollum et al. 2018). The restrictions on CO_{2eq} emissions impose an additional 20 % cost to the delivery of energy services. Costs increases are dominated by capital investments, followed by operation & maintenance costs, and welfare losses. On the positive side, there is reduction of expenditures in fuels, due to the rise in efficiency. There is also a rise in the "salvage value" (remaining value of assets by the end of the considered period). These results raise several considerations. First, as pointed out in other studies (McCollum et al. 2018), access to finance is likely to play a vital role to enable the transition. Second, operation and maintenance costs, which are rarely discussed, require more attention in mitigation studies. Third, the higher salvage value should not be a problem as far as it is not embedded in assets that difficult further decarbonisation. In the case under study most of the salvage value is on wind and hydropower plants, which are likely to be needed after 2050. Lastly, welfare losses (i.e. reduction of consumption due to higher prices) could take place and policies may be needed to make sure essential services are available for the most vulnerable sectors of society.

Integration procedure

Deep GHG mitigation targets would require profound transformations in the energy system. More than 600 processes of the energy system are to some extent affected by the GW mitigation target. When these are ordered by their contribution to changes in CO_{2eq} emissions, far fewer processes are needed to explain the bulk of the changes in CO_{2eq} emissions (Fig 6.3). The ecosystem quality and human health scores follow a similar stabilising trend, which implies that considering the changes in more processes will only marginally improve the accuracy of the results. The fact that a few processes drive changes facilitates the integration of ESOM and LCA results, since it limits the number of connections needed between both models. We hypothesise that this feature is influenced by the deterministic nature of the optimisation algorithm and the relatively low number of constraints imposed on the model.

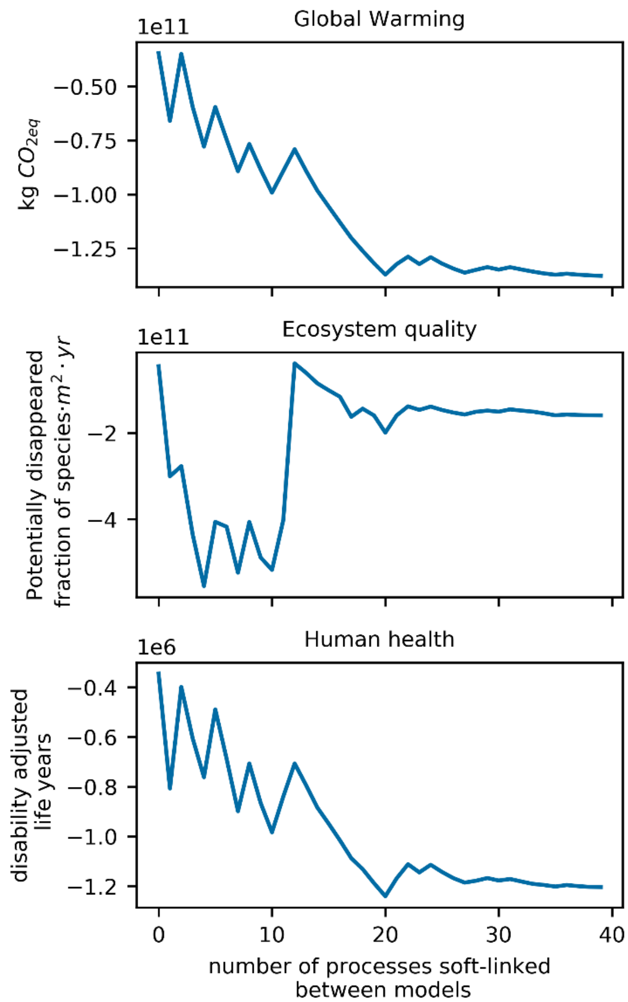

Figure 6.3: Cumulative environmental burden vs the number of processes considered in the assessment.

Processes ordered by their absolute contribution to changes in CO_{2eq} emissions. A few processes explain the bulk of the changes in burden. Cumulative contribution is negative, meaning that there is a reduction in environmental and human health impacts.

The use of NATEM efficiencies and emission factors and fuel switching changes the CO_{2eq} considerably compared to the original process, with relative CO_{2eq} emissions between 41% and 201% (Fig. B6 in supplementary information). Hence, harmonisation is an important step in the integration process. The harmonisation of combustion emission factors had a minor role (Fig. B9), suggesting that the ecoinvent database and the Canadian National Inventory report use consistent emission factors. A comparison between direct CO_{2eq} emissions in NATEM and the LCA validates the results of harmonisation (Fig. B8 in supplementary information). The comparison is grounded in the idea of 'common measurement points' where both models should render comparable results (Wene 1996). Direct combustion emissions are indeed very similar, and we attribute minor differences to differences in non-CO_2 GHG emission factors.

Some of the services such as freight transport are considered 'final demands' in ESOMs, but are intermediate services from a LCA description of production systems. Therefore, some changes in the energy sector, such as the electrification of freight transport, should in principle be considered in the modelling of processes using these services. We analyse the GW impact of all the processes in the supply chain that use services whose supply has changed. In our case, with the exception of electricity, the consideration of these 'feedback effects' marginally improves the accuracy of the results. Many of the services consumed rely on global supply chains, and changes in Quebec only marginally affect them. Nonetheless, we adapted the production of electricity and gas supply, among the most relevant feedback mechanisms (see Supplementary information notebook 6).

6.5 Discussion

Integrating ESOM and LCA gives a different perspective on energy transitions, observing several dimensions of the same interventions. It increases the robustness of the mitigation, quantifying if CO_{2eq} emissions would be really reduced and where. It quantifies impact on human health and the environment, and the principal mechanisms driving damage, helping to prioritise interventions. It also indicates the cost of the transition and their nature, which are essential to craft socially acceptable policies.

Our case study suggests that the introduction of low carbon technologies would have positive effects on human health and the environment, which could facilitate the social acceptability of GW mitigation policies. The impact is driven by GW, water scarcity and land transformation, but also by a less well-understood factor: metal contamination. All these conclusions would not be possible with ESOM alone. Even if most of the deleterious effects are in the long-term, energy systems have been slow to change, and therefore, their transformation is increasingly pressing.

The integration method is applied to a case study in the province of Quebec and energy transition consequences, and costs could be different in other regions. For instance, Quebec has vast hydropower capabilities, which reduces the costs of the transition to low-carbon energy systems. However, most of the changes are associated with reduced use of fossil fuels, which are abundantly around the world. Therefore, similar co-benefits could also be found in other regions. NATEM-Quebec has a technological richness similar to other ESOM, and the same integration methods can be applied to other bottom-up technology-rich models. To that end, standardisation of output formats would facilitate multidisciplinary assessments, which are acutely needed.

6.6 Methods:

6.6.1 Study design

The potential consequences of low carbon technologies on a deep decarbonisation strategy of the energy system are analysed with an integrated ESOM LCA analysis. This study uses NATEM-Quebec, an ESOM of the widely used TIMES framework (Glynn et al. 2015). NATEM-Quebec is a simplified version of a larger model of the whole Canada (Vaillancourt et al. 2017). It has 2,110 processes and 333 energy commodities defined, therefore comparable to other large technology-rich ESOM. As in previous studies (Astudillo et al. 2017b), constraints have been kept to a minimum, to assess what is technologically possible, not what is likely to happen.

To interpret the results it is important to understand the model assumptions and principles (Sovacool et al. 2018). TIMES equilibrium model is grounded in assumptions of perfect market competition. Even if perfectly-competitive markets are just an abstraction that differs from real markets, it is a valuable approximation, because they point to options that minimise total costs, maximising 'utility', a measure of social welfare. TIMES models implicitly assume that all energy services are equally important and follow a utilitarian normative approach to propose "what should be done". Utilitarianism is grounded on consequentialism (actions are judged according to their consequences), hence analysis follows teleological ethical principles (Ekvall et al. 2005).

Scenarios in NATEM-Quebec are an evolution of those presented in Astudillo et al. (2017b). The model has been improved iteratively, concentrating on the technologies that had a more significant role in the change in CO_{2eq} emissions. The transport sector is a main contributor, and a special effort has been made to better model and document this sector. Passenger transport powertrains have been parameterised based on the THELMA project (Bauer et al. 2015; Del Duce et al. 2016). The efficiency of the powertrains is a function of vehicle size, driving cycle and year of manufacturing (see Fig. B2 and associated explanations for details). Efficiencies of light freight trucks were estimated from THELMA results, considering the extra weight of the cargo (Fig. B3). Airplane efficiency is derived from a study characterising future airplanes as a function of travelled distance, year of manufacturing and plane type (Cox et al. 2018). The processing of airplane data is documented in notebook 7. Road freight transport technologies are parameterised from a review of the literature (spreadsheet in supplementary information). Emission factors from fuel combustion have been updated using the latest report on GHG in Canada (Environment Canada 2017). The modelling of the electricity sector, including, the variability of renewable resources and emissions from electricity trade are documented in Astudillo et al. (2017b). CO_2 emissions from hydropower development have been updated considering the latest findings of the literature (Prairie et al. 2017).

Both scenarios have several constraints to represent technological limitations, such as the limited autonomy of battery-based vehicles. The mitigation scenario has an additional constraint on the CO_{2eq} emissions over time (Fig. B7). The Supplementary information provides a list of constraints as well as additional analysis of their effect on the solution.

6.6.2 ESOM – LCA integration

Times2bright is the software developed to preprocess, integrate and analyse results from TIMES models and the LCA databases. The software is divided in three libraries, preprocess, integrate and analyse and could be applied to other technology-rich models with similar structure. For the LCA component, it uses the LCA open-source software brightway2 (Mutel 2017). The results from TIMES are exported as spreadsheets and manipulated with times2bright with a series of functions and procedures. Electronic notebooks documenting all the soft-linking are available in Supplementary information.

A screening process is implemented to simplify the soft-linking. The processes that contribute more than 1% to the absolute changes in GW emissions as accounted by the TIMES model “pass” the screening and are included in the analysis with their full life cycle inventory. If a process that passes the screening is an intermediate process, the demand for that process arising from the rest of the processes included in the analysis is subtracted. The subtraction is done to avoid double-counting environmental burden. The alternative approach to avoid double-counting proposed by Volkart et al. (2018) is also valid but more difficult to implement with the screening algorithm, since fuel imports do not have associated emissions. Limiting the analysis on the most contributing processes reduces exponentially the number of processes that need an LCA equivalent.

NATEM-Quebec provides a more representative modelling of future technologies and efficiencies than the LCA database ecoinvent, which model current technologies. Therefore, efficiencies and emission factors are harmonised to conform to NATEM values. The life cycle inventory of most of the processes is created modifying existing datasets of the consequential version of the ecoinvent database (Wernet et al. 2015) (v3.5). Among the GHG considered in NATEM (CO_2, CH_4 and N_2O), CO_2 was by far the most important (Fig. B4 in supplementary information). Therefore, only CO_2 emission factors were harmonised, that is, the CO_2 combustion emissions per unit of fuel are the same. Harmonising efficiencies and emission factors ensures that direct emissions CO_2 emissions are the same in NATEM and the LCA. “Indirect” source of emissions were updated if they had a large contribution to total impact and their modelling differ between ecoinvent and NATEM. In our case the marginal electricity mix was updated for this reason, using the values of NATEM. Proxies and necessary parameters to harmonise efficiencies and CO_2 emission factors are identified first (Notebook 1) and compiled in a csv file. Fuel use and associated emissions are harmonised in notebook 3. To scale emissions we assume that all airborne emissions are due to fuel combustion, which is clearly the case for most of the technologies (Simons 2016) (see notebook 3). A workflow to update fuel use and emissions from different fuel mixes (e.g. electrification or higher biofuel content) is encoded in notebook 3. Some processes did not have a clear equivalent in the LCA database. In such cases, processes are defined from NATEM exchanges, using a semi-automated procedure (notebook 2).

A procedure to quantify relevant structural “background” changes is detailed in notebook 5). The procedure uses the matrix representation of supply chain used in LCA to systematically analyse the impact of changes in services (e.g. heavy freight transport) on the entire supply chain. Changes in the electricity supply chain were identified as the most important and consequently updated (notebook 3).

6.6.3 Impact assessment

The environmental impact is assessed with Impact World + (Bulle et al.; CIRAIG et al. 2017) (v1.4.1), state of the art in impact assessment methods. Impact World + is the updated version of the widely used Impact 2002+ (Jolliet et al. 2003). The default version uses world-average conditions to determine characterisation factors, but regionalised factors are also available.

Following best practices (Patouillard et al. **2018**), regionalised characterisation factors were used for flows with the highest contribution to environmental impact. In our case, water-flows from hydropower are based on regionalised characterisation factors, as almost all of them take place in Canada, a region with below-average water stress problems (notebook 6). Impact World + results differentiate between long-term and short-term effects, which is recommended practice in LCA (UNEP-SETAC 2016). Discounting is a contested matter in GW mitigation (Nordhaus 2007; Stern 2016) but rarely discussed in LCA. When aggregated (Fig 6.1), we assume that they are equally important. Other discounting approaches are possible, and they are likely to affect persistent pollutants such as CO_2 and metals since previous research has shown that the choice of time horizon can have a large influence for persistent pollutants (De Schryver et al. 2013).

Direct impact is calculated as the sum of operating emissions of all the processes that define the demand for energy services. The calculation uses the matrix formulation of LCA, summing the columns that correspond to demand of the characterised inventory matrix. See notebook 6 for details. Indirect emissions are the difference between total and direct emissions. Indirect emissions match what is typically not accounted on ESOM.

The procedure is written in an open-source language and documented in electronic notebooks to facilitate reproducibility (Sandve et al. 2013). When possible, existing software was used (Hunter 2007; McKinney 2010; Mutel 2017), and internal validation procedures were added to avoid errors. Assumptions and constraints have been kept to a minimum, aiming for parsimony (DeCarolis et al. 2017). Input data has been iteratively refined, aiming to improve data quality (Astudillo et al. 2017a).

Data availability: Extensive information on the scenario data and assumptions of NATEM-Quebec is provided in the supplementary information. The notebooks documenting the analysis are available for reviewers only at open science framework site (https://osf.io/w94xr/?view_only=81ac50b2bb784542b70926abfd0e56b6) The link also contains the entire code of times2bright, written under an open-source license. Times2bright code and notebooks will be made publicly available if the manuscript is accepted.

CHAPTER 7: CONCLUSIONS AND FUTURE WORKS

7.1 Conclusions (Français)

Les réponses aux questions posées lors de la revue de littérature constituent l'apport original de cette thèse. Les conclusions peuvent être divisées en deux catégories : spécifiques au Québec (section 7.1.1), qui sont pertinents pour les politiques énergétiques régionales, et méthodologiques (section 7.1.2), plus pertinents pour la partie ACV et modélisation des systèmes énergétiques.

7.1.1 Conclusions spécifiques pour le Québec

Cette thèse répond à des questions pertinentes sur les politiques énergétiques régionales, qui peuvent être résumées comme suit.

• *L'introduction de technologies à faibles émissions de carbone, auraient-elles des impacts négatifs imprévus par NATEM*? Nous trouvons qu'une stratégie de réduction de GES basé sur l'optimisation de coûts n'augmente pas les impacts sur la santé humaine ou la biodiversité. Au contraire, NATEM et MOSE limités à des émissions de combustion peuvent sous-estimer les réductions d'émissions de GES. L'ACV montre que les réductions d'émissions de GES provenant de la chaîne d'approvisionnement de combustibles fossiles compenseraient les augmentations d'émissions associées à l'augmentation de la production d'électricité renouvelable.

• *Quels sont les mécanismes environnementaux qui affectent le plus la santé humaine et la biodiversité ?* La transition énergétique apporterait des réductions des impacts nocifs sur la santé humaine, principalement par le biais d'une réduction de la pénurie d'eau, du réchauffement planétaire et des émissions carcinogènes. La transition énergétique réduirait les impacts sur la biodiversité, en réduisant le réchauffement planétaire, bien qu'une utilisation des terres par l'hydroélectricité affecterait les écosystèmes locaux.

• *Quels sont les coûts potentiels de la transition énergétique ? Dans quelle mesure une planification urbaine différente aurait une incidence sur les coûts de transition* ? La politique de réduction de GES pourrait entraîner une augmentation des coûts de 20%, bien que ces coûts puissent être beaucoup plus bas avec une utilisation plus intensive des transports en commun. L'augmentation des coûts entraine une hausse des prix, ce qui devrait être pris en compte pour garantir l'acceptabilité sociale, particulièrement pour les services énergétiques les plus essentiels. La transition énergétique augmenterait la demande d'infrastructure, et cette infrastructure aurait une valeur résiduelle à amortir après 2050. Des centrales éoliennes et hydroélectriques sont le principal actif à amortir après 2050. Cela ne devrait pas poser de problèmes, car c'est le type d'infrastructure nécessaire pour continuer la réduction de GES.

• *Des bâtiments mieux isolés constitueraient-ils une option d'atténuation rentable ?* Oui, les codes du bâtiment avec des exigences « plus strictes » pour les bâtiments neufs réduiraient le coût total de réduction de GES. Cependant, changer l'isolation des maisons existantes est souvent trop coûteux.

• *Comment réduire les émissions à long terme du transport routier ?* Les moteurs électriques sont les plus rentables pour réduire les émissions des transports routiers à long terme, tandis que les biocarburants de deuxième génération peuvent être utilisés à moyen terme. Le moteur à gaz naturel, considéré comme la voie à suivre dans les politiques régionales pour le transport de marchandises, n'est pas la meilleure solution d'après nos scenarios. Les camions électriques semblent être une option viable pour les corridors achalandés.

• *Quels systèmes de chauffage devraient être utilisés pour réduire les coûts de la transition énergétique ?* La pompe à chaleur adaptée au climat froid est la technologie optimale pour chauffer les ménages québécois et réduire les GES.

• *Si les GES provenant de la création des réservoirs sont pris en compte dans NATEM, cela affectera-t-il la solution optimale* ? Lorsque les émissions de CO_2 provenant de la création des réservoirs sont prises en compte, d'autres technologies renouvelables deviennent la solution privilégiée pour réduire les GES.

• *Les facteurs d'émissions de combustion de l'inventaire canadien des GES sont-ils cohérents avec les valeurs de la basse de données ACV « ecoinvent »* ? Oui, pour les processus évalués, les facteurs d'émission de CO_2 sont similaires, avec des différences maximales inférieures à 5%. Les émissions de combustion de CH_4 et de N_2O jouent un rôle minimal dans le budget total d'émissions, à l'exception des émissions de CH_4 des véhicules à gaz naturel.

• *Qu'en est-il de la production d'énergie renouvelable variable (éolienne, solaire et au fil de l'eau) et l'importation d'électricité disponible pendant les périodes de haute demande en hiver ?* Les centrales au fil d'eau, solaires et éoliennes ont leur production maximale en printemps, été et automne respectivement. Par conséquent, l'approvisionnement d'électricité en hiver est très dépendant des barrages hydrauliques. Les importations d'électricité en hiver venant de Churchill-Falls sont particulièrement importantes.

7.1.2 Conclusions spécifiques à la méthodologie ACV et modélisation des systèmes énergétiques

L'intégration du modèle NATEM aux méthodes d'ACV permet de tirer plusieurs conclusions généralisables à d'autres modèles TIMES. Ces conclusions sont également applicables aux autres modèles d'optimisation des systèmes énergétiques comme MESSAGE ou OSEMOSYS.

• L'utilisation d'une approche « cut-off » réduit de manière exponentielle le nombre de processus à jumeler entre les modèles TIMES et ACV, réduisant ainsi la complexité de l'intégration des modèles.

• Il y a des gains importants d'efficacité prévue dans les années à venir. La transition énergétique entraine aussi une augmentation de l'utilisation des biocombustibles. Ces changements ont un impact important sur l'empreinte carbone des technologies et doivent être pris en compte dans l'inventaire ACV.

• L'intégration des modèles d'optimisation des systèmes énergétiques et l'ACV permet une évaluation des effets potentiels sur la santé humaine et la biodiversité des transitions énergétiques. Ces indicateurs additionnels réduisent la possibilité d’avoir des effets nocifs non prévus par les modèles d’optimisation.

• Les changements dans la chaine d’approvisionnement des services énergétiques ont des effets de rétroaction non modélisés par le modèle TIMES et ces boucles de rétroaction devraient être incluses dans les inventaires d’ACV. Cependant, ces boucles n’ont pas forcément des effets importants sur l’inventaire et une priorisation basée sur leur empreinte carbone faciliterait l’actualisation de l’inventaire d’émissions.

• Les modèles d'optimisation des systèmes énergétiques tels que TIMES permettent une analyse des coûts bien poussée, complétant ainsi les résultats environnementaux.

• La liaison entre modèles d'optimisation des systèmes énergétiques et la simulation du bâtiment permettent de prendre en compte les couts de réduction de GES à long terme. Ces couts devraient être pris en compte lors de l’établissement des niveaux d’isolation minimaux dans les codes du bâtiment.

• Les données ouvertes ont un grand potentiel pour améliorer la paramétrisation des modèles des systèmes énergétiques et de l’ACV.

• La segmentation de la demande des modèles TIMES peut avoir une très grande influence sur les coûts de réduction de GES, et les stratégies axées sur la demande peuvent s'avérer particulièrement efficaces.

7.2 Conclusions (English)

The response to the questions raised during the literature review constitute the original contributions of this thesis. Conclusions can be divided between those specific to Quebec, which are relevant for regional energy policies, and those that are methodological, which are relevant for the practice of LCA and energy system modelling. Section 7.2.1 describes the main Quebec-specific conclusions, and section 7.2.2 details methodological insights.

7.2.1 Quebec-related conclusions

This thesis has answered a number of questions that are relevant for regional energy policies, which can be summarised as follows.

- *Would the introduction of low-carbon cost-optimal technologies result in negative impacts unforeseen by NATEM?* We find that a cost-optimising mitigation strategy would not ‘backfire’ (i.e. result in higher impacts on human health or biodiversity). Instead, it would reduce the burden on both areas of concern. Moreover, NATEM and similar ESOMs could underestimate the GHG emission reductions of the mitigation policy. The LCA shows how GHG emission reductions from fossil fuel supply chain would outweigh increases in emissions associated with the increase in renewable electricity generation.

- *What are the environmental mechanisms driving the changes in environmental impact?* GHG mitigation would bring net benefits to human health, mainly through reduced GW and water scarcity and carcinogenic emissions. GHG mitigation would reduce the impacts on biodiversity, through reduced global warming, although increased land-use from hydropower would affect local ecosystems.

- *What are the potential costs of the energy transition? How different urban planning would affect transition costs?* The mitigation policy could raise costs by 20%, although these costs can be much lower with changes in demand such as higher use of public transport. These changes involve different urban planning. The increase in costs is driven by investment needs and maintenance costs, although there is a rise in welfare losses due to rising prices, which should be considered to ensure social acceptability. The mitigation policy would push to have infrastructure with a salvage value after 2050, mainly wind and hydropower plants. This is not likely to be problematic because it is the kind of infrastructure that would facilitate further reductions of GHG. It would be if they were embedded in long-lasting stranded assets with no use for further mitigation.

- *Would better-insulated buildings be a cost-effective mitigation option?* Building codes with 'tighter' requisites for building envelopes of new buildings would reduce the total costs of climate change mitigation, but changes in existing houses are often too expensive.

- *Which powertrains are the cheapest options to reduce emissions in the long-term?* Electric powertrains for passenger road and freight transport are the cost-optimal technologies to reduce transport emissions in the long-term, while second-generation biofuels are used in the medium term. Natural gas power trains, seen as the way forward by the regional government, do not appear in GW mitigation scenarios. Electric trucks powered by catenaries appear to be a viable option for busy corridors.

- *Which heating systems should be used to reduce societal costs?* Air-based cold climate heat pumps are the cost-optimal technologies to heat households in Quebec, despite being less efficient in cold climates.

- *If GHG from reservoir impoundment are considered in NATEM, would it affect the solution?* When CO_2 emissions from reservoir impoundment are considered, other renewable technologies become the preferred solution to reduce GW at minimum costs.

- *Are combustion emission factors from the Canadian inventory of GHG coherent with ecoinvent values?* Yes, for the processes evaluated emission CO_2 emission factors are similar, with maximum differences of less than 5%. CH_4 and N_2O combustion emissions play a minimum role, with the exception of CH_4 emissions from vehicles.

- *How does the generation of variable renewable energy (wind, solar and run-of-river) and imports match the electricity demand, concentrated in winter?* Peak electricity supply is very dependent on imports from New Foundland. Run-of-river plants have their natural flow reversed, producing more in winter because of upstream reservoir plants. Wind plants have their lowest production in summer, when they are less needed.

7.2.2 Conclusions related to LCA and energy system models

The integration of the TIMES model NATEM with LCA methods allows to draw several wider conclusions on the integration of TIMES models and LCA. These conclusions are also applicable to other bottom-up ESOMs.

- The use of an explicit cut-off rule reduces the exponentially the number of processes that need to be mapped between TIMES and LCA models, reducing the complexity of mapping two large bottom-up models.

- There are expected large differences between existing and future technologies. Adapting the efficiencies and fuel shares results in important changes in their environmental impact and it is an important step to improve technological representativeness.

- Integrating ESOM and LCA increases the robustness of the mitigation plans, minimising the possibility of deleterious environmental side-effects and helping to plan interventions.

- Quantifying the feedback effects (i.e. the effects of changes in what TIMES models considers final demands and LCA intermediate services) allows prioritising model updates.

- ESOMs like TIMES allow a powerful and to date unexplored analyses of costs, complementing the environmental results. These analyses include the analysis of potentially stranded assets, the nature of mitigation costs and their magnitude.

- Linking ESOM with building simulation can be effectively used to model costs and energy saving of changing building envelopes.

- ESOMs technologies can be characterised from a variety of sources, benefitting of the collaboration between researchers and use of open-data platforms [4].

- The segmentation of demand of an ESOM can be very influential on the total mitigation costs, and demand-side strategies may prove particularly effective to reduce mitigation costs.

7.3 Future works

Insights should be understood considering that models are just a simplification of reality, which is considerably more complex. In this thesis I have tried to explore the underlying assumptions and principles of the models underpinning the assessment, aiming to give a more nuanced interpretation

[4] Examples in this thesis include the use of data from (Swan et al. 2009; NRCan 2013; Bauer et al. 2015, 2016; General Electric International 2016; Cox et al. 2018).

of results. In this section I attempt to foresee future lines of work associated with both ESM and LCA.

An area that requires more attention is the linking of processes that are final demands for ESOM but intermediate products in LCA, which can cause double counting or accuracy losses. Examples include freight transport and energy for different industries such as aluminium production or cement. This thesis includes a procedure to prioritise linking based on the reference product and locations of the activities. In the case of Quebec, the contribution to GHG of feedback effects is rather small and additional linking between "reference flows" and the product system model are not needed, but in other cases further linking may be needed. Further linking requires a better understanding of the location and the services provided by the product system. With respect to location, current inventories are very vague about where activities take place. For example, will truck manufacturing take place in the region under study and therefore be affected by changes in energy supply? many processes such as automotive manufacturing, rely on global supply chains, with different components done in different countries, therefore modelling geographically explicit "accurate" supply chains is very challenging. Understanding the service provided by final demands is also necessary. Here the aggregated nature of some energy demands in NATEM (e.g. energy use by "other industries" makes it very difficult to identify which LCA datasets should be modified. The lack of detailed statistics also complicates the analysis of potential improvements. To this end, a more precise disaggregation of energy demands in industries would be useful. As pointed in Astudillo et al. (2017b), in Canada there is a lack of statistics about the industrial sectors complicating the study of mitigation opportunities.

The disaggregation of final demands is another of the limitations of models that require further analysis. Results in Astudillo et al. (2017b suggest that different segmentation (e.g. more public transport) results in very different mitigation costs, therefore, when using an ESOM for planning, alternative scenarios with different demand measures should be actively explored. This recommendation is in line with the increasing interest by the IPCC on demand-side solutions (Creutzig et al. 2018; Grubler et al. 2018). Questioning demand segmentation also questions the purpose of ESOM. Usually ESOMs do not claim to have a predictive purpose but rather a normative one. However, demand segmentation has been introduced to represent consumer preferences and provide more "realistic" results. Therefore, current ESOMs like NATEM are not purely normative nor explicative but something in between.

The predictive capabilities of ESOMs also require further investigation if they are to be used for CLCA. An ALCA of a normatively defined future does not challenge the capabilities of ESOMs because there is no claim about the likelihood of this future taking place. However, ESOMs assumptions on optimisation cannot be easily "abstracted" in the consequential analysis. The consequential assessment with an ESOM answers what would be the consequences of changes in the system under perfect competitive market conditions. These consequences are only likely if cost-optimisation is likely to be observed. Real-world transitions of the electricity sector in the United Kingdom have been shown to be in the range of near-optimal scenarios (Trutnevyte 2014), therefore, cost-optimal solutions seem to be a reasonable first-approximation of real-world transitions. However, more analyses like the one conducted by Trutnevyte (2014) are needed to understand if her conclusion can be extended to other sectors or countries. Moreover, near-optimal scenarios may have very different environmental impacts than the cost-optimal one, particularly if there are not bound by GHG emission constraints.

The topic of near-optimal scenarios is closely linked to the analysis of uncertainty, an important issue not addressed in this thesis. Uncertainty estimates are often divided in epistemic (e.g. associated with the quality of the data) or "inherent" and the works of this thesis can be used to reduce both. This thesis improved data quality on both the TIMES model and the LCA database, updating data sources and harmonising parameters. The adaptations would mean lower epistemic uncertainty, however, for the non-updated parameters, epistemic uncertainty would be larger. For example, NO_x emissions from combustion are likely to decrease as pollution control technologies improve, but these improvements are not modelled, and temporal representativeness would be poor. In LCA epistemic uncertainty is estimated with the pedigree approach, and best practices have suggested using the same procedure to assess epistemic uncertainty of ESOMs (DeCarolis et al. 2017). Some ESOM researchers start to apply it and 'discover' critical assumptions (e.g. (Pye et al. 2018)). However, one should keep in mind that the pedigree coefficients were not thought to be used in long-term prospective assessments and may need to be adapted. It is not clear that current scores capture the magnitude of the error introduced by using non-representative data in long-term prospective studies. On top of the epistemic uncertainty, the "inherent" uncertainty has not been addressed in this thesis. In some cases, the inherent uncertainty would be easily quantifiable. For instance, the capacity factors of renewable energy per time slice were only characterised by their average value, but their standard deviation would be straightforward to calculate, and it could be used on stochastic runs of TIMES models. For other parameters, such as future prices of natural gas extraction, uncertainty estimation is more challenging. Uncertainty from value-choices (e.g. the choice of a particular process as a proxy) could be also integrated. Finally, uncertainty introduced by the impact assessment phase is also large but recent advances have been made to introduce it in TIMES-LCA assessments (Patouillard 2018).

Exploring a range of possible futures would require a further level of automatization of the workflow used in this thesis, and it may require altogether a different approach, as it would be excessively time-consuming to run the same procedure several thousand times. Other approaches will also be needed if LCA indicators are used in the ESOM. As mentioned in Astudillo et al. (2018), this requires a one to one mapping of activities or optimisation will be biased. To date, one-to-one mapping is limited because matching is done by name resemblance, which is prone to errors. One potential way to improve this is to classify activities and flows using common "taxonomies". A clear candidate is the "standard international energy product classification" for energy flows. This is the classification used by many countries, including the energy balances that underpin the calibration of NATEM.

It is also important to reflect on the "added value" of incorporating LCA, and if ESOMs alone are sufficient for climate change mitigation plans. Most of the GHG were captured by NATEM-Quebec, and the ones that did not come from fossil fuel extraction and transport. These "underreported" GHG reductions would be captured by a multiregional ESOM including fossil fuel extraction (such as NATEM-Canada). Impacts on human health and ecosystems are also mostly due to climate change reductions. Therefore, in our case the added value of LCA was limited. More case should be analysed, particularly in regions with fewer hydropower resources where use of biofuels may be more acute and for the other impact-pathways of relevance, water scarcity and ecotoxicity. The LCA field should strive to be useful for decision making if it wants to be relevant as an environmental assessment method.

Finally, there is much work and important work to do on model reproducibility, reusability and validation. Currently, it is difficult to re-use the results from LCA and ESOM models for further analysis (Kuczenski et al. 2018; Vandepaer and Gibon 2018), resulting in a tremendous waste of resources. A first step to facilitate data reuse would be to provide results in a machine-readable format and under a permissive license when possible. For instance, some organisations such as IEA-ETSAP already share publicly reference information on characteristics of technologies, but it would be more easily used if it was provided as machine-readable tables. The IAMs community has faced criticism on the transparency of the models underpinning IPCC results and now has developed a standardised output format for their results (Huppmann et al. 2018). These are steps in the right direction, facilitating model comparability and data re-use. In this thesis I have tried to follow best practices on scientific computing, creating a reusable python library to compute common operations, and documenting all the steps in electronic notebooks and creating validation procedures to detect errors. However, the methods have not been tested in other ESOMs which will probably require adaptation of the code. The reproducibility is also limited by the use of proprietary data in the ESOM and LCA databases. To have more transparent, reproducible and reusable models the research community should build the tools to reuse publicly available data and raise the standards on model reproducibility. For this to happen cultural and structural shifts are needed, including but not limited to the collection and disclose of statistics with permissive licenses for re-use.

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Annex A Supplementary material chapter 5

A.1 Datasets

This study compiled a series of datasets to conduct the analysis. The section documents the origin of the datasets and the data handling. Most of the data come from recent years, except runoff data from rivers, as only older data are available. We do not expect that annual river flows have substantially changed.

- Dataset A: The CSDDRD database for single and double-row houses in Quebec (Swan et al. 2009). It includes the characteristics of 2880 detached houses in the Quebec province. Each dwelling is defined with 446 parameters, providing a complete description for conducting building simulation.

- Dataset B: Hourly electricity demand, exports and imports in Quebec for the period 2008-2015. The data was obtained from Regie d'energie (Régie de l'énergie Quebec), mostly in pdf format which we transformed into a machine-readable format.

- Dataset C: Hourly electricity imports and exports from Quebec for the year 2015 by adjacent region. Data comes from the system operators of adjacent regions (New York, New England, New Brunswick and Ontario). Data for New-Foundland and Labrador was calculated subtracting imports from New York, New England, New Brunswick and Ontario from total imports (dataset B).

- Dataset D: Hourly temperature data in Montreal for years 2009-2015. The data was retrieved from a governmental website (Govt. of Canada 2016a), which provides bash commands to download historical data from different weather stations in CSV files. Data processing is documented in (Astudillo 2017).

- Dataset E: Daily run-off from different hydrological stations across the region. We covered the rivers St. Laurent, Betsiamites, Outardes, Manicouagan and Outaouais between years 1978-1994. These rivers contain a large share of the existing ROR capacity of Quebec. The data was retrieved from a governmental software that facilitates the access to the HYDAT database of hydrometric data across Canada.

- Dataset F: Simulated hourly wind production data for 1382 potential sites for wind power expansion in Quebec between years 2008-2010. The data was made available by the Canadian Wind Energy Association (CanWEA) as part of the Pan-Canadian wind integration study (PCWIS) (Canwea 2016). For consistency, we used just the sites included in the 35% wind power penetration scenario, which was chosen as maximum yearly penetration levels.

- Dataset G: Hourly solar irradiation in Montreal from the Canadian weather energy and Engineering datasets (SWEEDS) (Govt. of Canada 2016c). This dataset provides typical solar irradiation data for different locations across the country.

The data handling for the publicly available datasets (D,E,F and G) is documented in (Astudillo 2017).

A.2 NATEM-Quebec model

NATEM-Quebec is a multisector model, which allows identifying global warming mitigation costs from a comprehensive perspective. The following subsections explain the modelling of the different subsectors.

A.2.1 Transport

The end use demands of energy in the transport sector are disaggregated in 20 transport modes. It includes passenger and freight transport using roads, rails, air and marine ways (Table 8 in (Trottier energy futures project 2016)). Each transport mode can be supplied by different technologies, including those using biofuels and electricity options (Table 9 in (Trottier energy futures project 2016))**.**

A series of technical constraints and environmental policies are modelled:

Energy efficiency targets: (CAFE standards) see Table 10 in (Trottier energy futures project 2016).

Federal legislation on renewable fuel requirements: conventional vehicles should use a minimum of 2% of biodiesel and 5% of ethanol.

A limitation to 1st generation biofuels in trucks: Share of first generation biofuels limited to 10% due to observed problems in cold weather.

Share gasoline/diesel: For buses and trucks, the share of use between gasoline and diesel is expected to remain constant.

Hybrid vehicles: Hybrid vehicles can just get a fixed percentage of energy from electricity.

A.2.2 Industry

The industrial sectors are classified as following the disaggregation of national statistics (NRCan 2013).

- Pulp and paper
- Iron and steel
- Aluminium smelting and refining
- Cement production

- Chemicals
- Other manufacturing
- Other industries
- Mining industries

The share of energy use in the form of electricity for each industrial sector is based on the maximum share of electrification of the same sector in other Canadian provinces. This constraint was derived from the version of NATEM that covers the whole Canada (Trottier energy futures project 2016), and it is considered to be a conservative assumption. The minimum share of non-electric energy sources is fixed to 65% of the share at the start of the simulation period. A sensitivity analysis explores the effects of relaxing these constraints (Fig. A11).

A.2.3 Agriculture

The agricultural sector models the energy demands associated with the production of 9 agricultural commodities: grains and oilseeds, dairy, beef, pork, poultry, eggs, fruits, vegetables and "others".

Similar to the case of the industrial sector, it is assumed that energy demands cannot be further electrified. Thus the minimum share of energy coming from electricity is constant during the simulation period. The minimum share of other energy sources for 2050 is fixed at 50% of their market share in 2011.

A.2.4 Commercial

The commercial sector includes demands for space heating and cooling, water heating, indoor and outdoor lighting, auxiliary equipment, auxiliary motors and “other services”. This segmentation mimics the disaggregation available on national statistics (NRCan 2013).

A.2.5 Residential

The energy demand in the residential sector is divided into 19 final energy services. Space cooling and heating for the four housing types (single-detached, apartments, attached houses and mobile homes) and other common energy services to all housing types: water heating, lighting, refrigeration, freezer, dish washing, cloth washing, cloth drying, cooking and “other electric equipment”.

A.2.5.1 Heating technologies and conservation measures

The costs and efficiencies of several technologies have been updated with respect to the values of NATEM (Vaillancourt et al. 2017). Efficiencies of combustion heating equipment have been adapted to be expressed in low heating value basis (LHV). Changes and literature sources are available in Table A1. The AF of heating equipment is calculated as the coefficient between average heating degree days and maximum observed heating degree days during a 7 years period.

Our proposal gives very similar results that alternative methods (Papakostas et al. 2009). All the calculation and data manipulation are available for transparency purposes (Astudillo 2017).

Given the importance of heat pumps on final results an additional sensitivity analysis explores the possibility of heat pumps being less efficient than predicted (Fig. A11).

Table A1 Characteristics of heating technologies (2011-2050)

Description	Costs (CAD/ kW)	Efficiency (LHV)	Lifetime	Source
Oil furnace	102-120	85-88%	20	(R. S. Means company 2015)
Biomass stove	539	72-85%	21	(EIA 2015)
Pellet stove†	321	92-103%	21	(EIA 2015)
NGL fireplace	150	62-76%	21	(R. S. Means company 2015)
Nat. Gas furnace	191	99%-108%	21	(R. S. Means company 2015; EPA 2017)
Natural gas heat pumps	807	113%-156%		(EIA 2015)
Geo. Heat pumps††	2800 (2012) 1820 (2050)	(SCOP) 4.12 (2012) 5.36 (2025)	38††	(Canadian GeoExchange Coalition 2010; IRENA and IEA 2013; Tamasauskas et al. 2013)
Air cold climate heat pumps	855 (2012) 556 (2050)	(SCOP) 2.38 (2012) 3.1 (2025)	18	(IRENA and IEA 2013; Tamasauskas et al. 2013; R. S. Means

				company 2015)
Solar combisystems	10660	2.08	40	(Cheng Hin and Zmeureanu 2014)

The variability in efficiencies and costs is due to technological progress in the simulation period and different qualities. † Relation low to high heating values from pellets comes from (Telmo and Lousada 2011). ††We considered the lifetime of the heat exchanger (the additional cost of renovating the heat pump is included).

This study tested several conservation measures using the building simulation software Can-Quest (NRCan 2017). The baseline household is represented by the average characteristics of single detached houses in Quebec, as described in CSDDRD database (Swan et al. 2009). The database includes total thermal resistance values but not the components of the envelope. The components were thus derived from typical compositions described in Can-Quest. Energy savings were calculated comparing the annual energy consumption of the baseline house with the consumption of the house with the conservation measure. The selection of insulating material is based on recommendations of the US Department of Energy (DOE 2017) and summarised in table A2. The house had a floor surface of 109 m^2 (dataset A), and was heated at 21ºC. The air-tightness corresponds to the average value of the housing stock (Fig. B2). We assumed the basement was heated, which is common practice according to survey data (NRCan 2011). The gross window area and average thermal conductivity of the building envelope (Table A3) come from the summary data of the CSDDRD database provided in (Swan et al. 2009).

These measures are summarised in Table A2. Costs were based on the RSmeans database (R. S. Means company 2015) and include material costs, labour installation costs plus overheads and profits. A regional modifier is applied to consider regional differences in labour and material costs. As for the rests of the technologies, sales taxes are not included. Further details can be found in Ref. (Pedinotti-castelle 2017) (in French).

In Table A3 the maximum thermal resistance that had a full uptake for each conservation measure is compared with reference thermal resistance values from existing building codes and IEA recommendations.

Table A2: Main parameters of the conservation measures.

Description	Component	Cost (CAD)	Energy savings (% of annual dmd.)	Total thermal res. (m^2 K / W)	% of installed capacity in consrv scenario
Replace interior insulation by batt R38 (9 in)	Roof	3190	8.2%	6.9	0%
Replace interior insulation by batt R38 (8 in) (new houses)		680	8.2%	6.9	100%

Add R20 panel (4 in)		3360	9.2%	7.6	0%
Add R21 panel (3 in)		3420	9.2%	7.8	0%
Add R20 panel (4 in) (new houses)		2320	9.2%	7.6	100%
Add R14 exterior panel (2 in)	Main wall	5820	14.4%	5.0	0%
Add R14 exterior panel (2 in) (new houses)		2170	14.4%	5.0	100%
Add R8 exterior panel (2 in)		5150	12.1%	3.9	0%
Add R21 exterior panel (3 in)		8975	16.1%	6.2	0%
Add R21 exterior panel (2 in) (new houses)		5270	16.1%	6.2	0%
Add R12 interior panel (3 in)	Basement wall	3180	11.8%	2.8	0%
Add R14 interior panel (2 in)		3100	13.8%	3.1	100%
Add R21 interior panel (3 in)		4930	18.4%	4.3	100%
Add R21 interior panel (3 in) (new houses)		3040	18.4%	4.3	100%
Double glass low-emission filled with argon	Windows	6960	9.1%	0.33	0%
Triple glazing windows		7950	1.8%	0.42	0%
Triple glazing, low emissions windows filled with argon		9030	12.9%	0.48	0%
Triple glazing, low emissions windows filled with argon (new houses)		2950	12.9%	0.48	100%
Programmable thermostat	Thermostat	165	12.9%		100%

Constraints were imposed in such a manner that houses could not install more than one measure of the same component.

Adding more insulation was a cost-effective mitigation measure for several parts of the building envelope. There is also a substantial difference between the level of insulation of the existing stock and the recommended values. It should be kept in mind that energy savings with higher levels of insulation are non-linear and therefore the same marginal change in insulation levels can result in very different energy savings.

Table A3 Tested and recommended total thermal resistance values (m^2 K / W) of different components of the building envelope.

	roof	walls above ground	walls below ground	windows
Quebec E-1.1 2012 (Govt. of Québec 2017)†	5.30	3.4	2.2	0.35

IEA recommendation for 2020-2030 (IEA 2013b)	6.67	6.67		0.9
maximum value tested with full uptake	7.6	5.0	4.3	0.48
Average house tested	4.6	2.5	2.1	0.30

† The values of the Quebec building code correspond to houses in area A, which comprises major cities such as Montreal.

A.2.5.2 Comparison of recommended building envelopes for new houses and those of the existing stock

Fig. A1 and A2 illustrate the differences between the recommended values of building envelopes characteristics and those of the existing stock. We selected two of the most relevant parameters, air-tightness and thermal resistance of exterior walls.

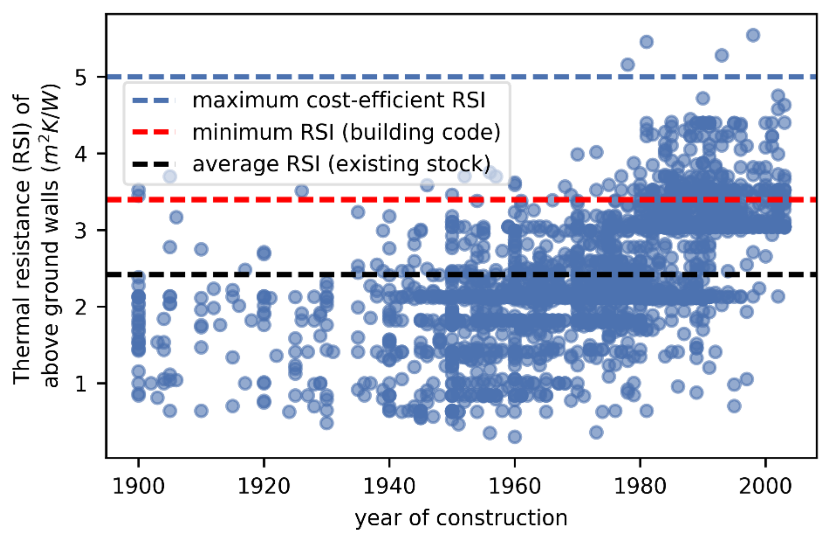

Figure A1: Thermal resistance of above ground walls of existing detached houses versus year of construction.

The dots are the entries in the CSDDRD database, representative of the existing stock. The horizontal lines represent the minimum values for new houses according to Quebec building code, the average value of the existing housing stock (Dataset A) and the maximum value that had a full uptake in NATEM. Houses constructed before 1900 were grouped due to confidentiality concerns.

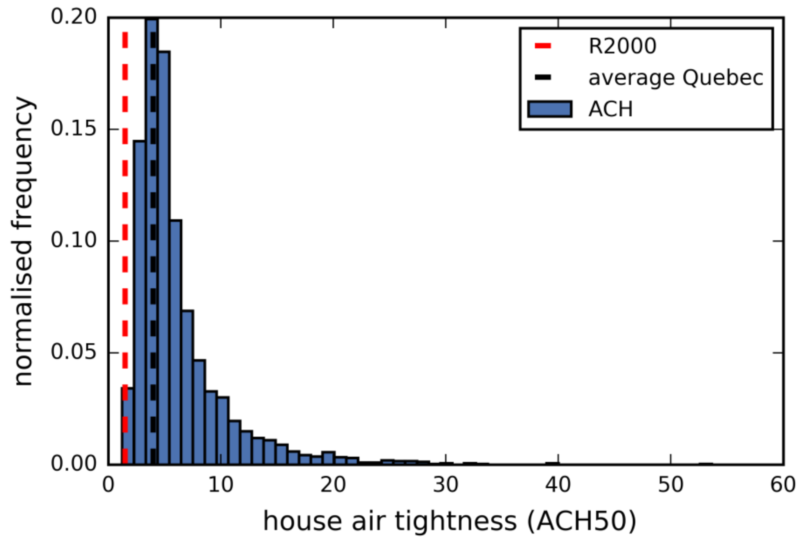

Figure A2: Normalised histogram of air tightness measurements (ACH50) of Quebec detached houses.

Data comes from dataset A. The air-tightness of the R2000 standard is drawn for comparative purposes.

A.2.5.3 Influence of heating on electricity demand.

The residential sector is one of the main consumers of electricity and the largest responsible of peak demand in winter (Fig. A3). Changes in electricity demand in Quebec are indeed largely explained by changes in outdoor temperature (Fig. A4).

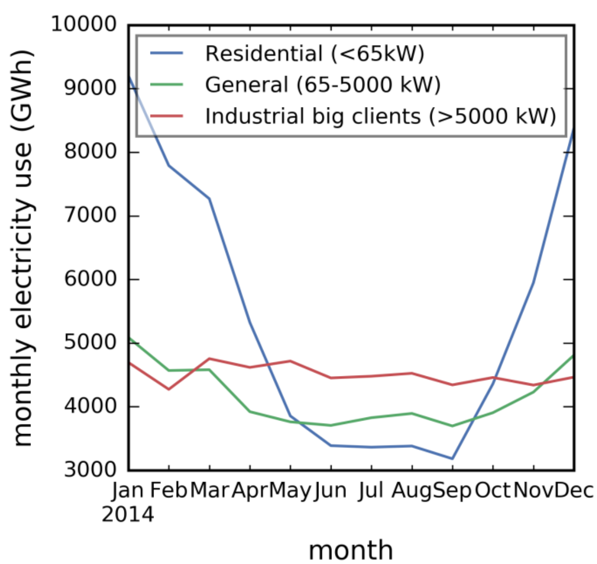

Figure A3: Projection of electricity demand by type of client in Quebec (2014).

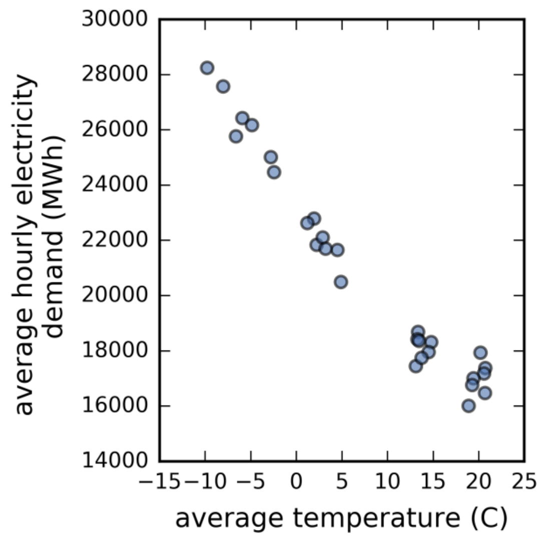

Figure A4: Hourly electricity demand in Quebec vs. average temperature (seasonal averages) (2008-2015).

Especially for seasons where heating is required (i.e. an average temperature below 18ºC), there is a strong linear correlation between electricity demand in Quebec and average daily temperature in Montreal (Fig. A4) which has a very similar heating profile that the main cities in the province (Fig A12).

In addition to the seasonal changes in electricity demand, there are important intra-day changes in electricity demand. The time slice divisions used intend to capture these changes (Fig. A5).

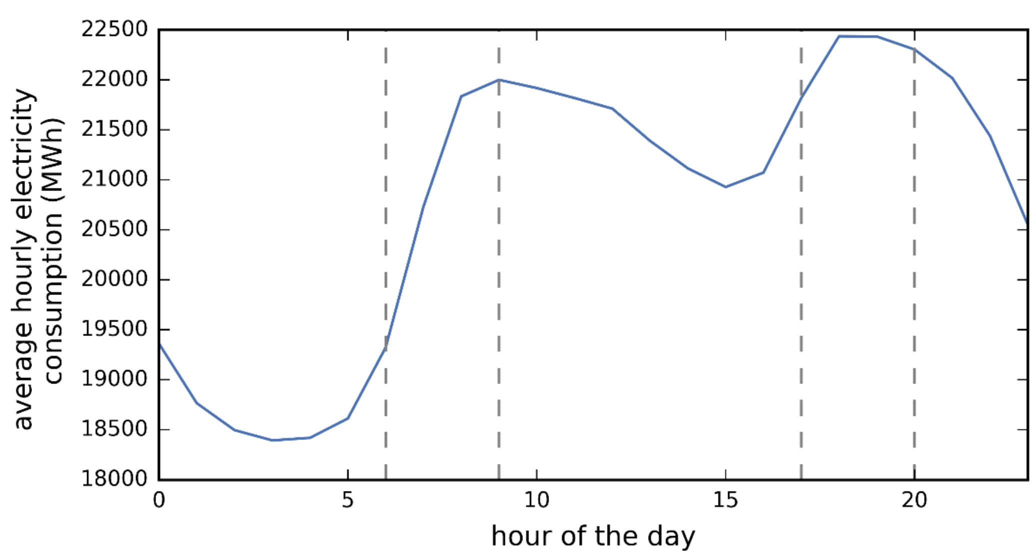

Figure A5: Electricity consumption per hour of the day (average for years 2008-2015). Dashed vertical lines mark the time slice divisions in NATEM-QUEBEC. Based on dataset B.

A.2.6 Electricity supply

Several technologies are available in NATEM-Quebec to model new electricity power plants. The main parameters are summarised in Table A4. Further details are provided in (Trottier energy futures project 2016). Cumulative potential for hydropower, geothermal and tidal expansion are available in Table 21 of (Trottier energy futures project 2016).

Table A4: New power plant technologies

	Invest. cost 2012 (CAD /kW)	Invest. cost 2050 (CAD /kW)	Fix. O&M costs 2012 (CAD /kW)	Fix. O&M costs 2050 (CAD/kW)	Var. O&M (CAD /MWh)	Lifetime (years)	Eff. (%)	Annual AF (%)
run-of-river	5486	5486	24	24		100	97	53
conventional dam large	4988	4988	17	17	0.63	100	97	53
wind onshore turbine conventional	2762	2072	68	53		30	100	38
solar photovoltaic fix 10mw	3731	1349	57	49		25	100	13
geothermal hydrothermal binary cycle	4362	4362	100	100	15.93	50	90	75
coal pulverized coal	3295	3295	26	26	1.05	35	38	86
coal integrated gasification combined cycle	4571	4571	47	35	1.46	40	40	86
nuclear reactor generation	8693	8693	145	145	2.04	40	32	85
tidal current sea generation turbine	7374	3682		128		25	100	30
biomass combustion fluidized bed boiler	5143	5143	106	106	1.06	30	35	75
landfill gas internal combustion engine	2104	2104	23	23	5.31	20	25	75
solid waste plant standard	8312	8312	393	393	1.06	30	26	75
wood pellet combustion fluidized bed boiler	5143	5143	106	106	1.06	30	45	75
heavy fuel oil steam turbine conventional	1727	1727	15	15	0.89	35	30	60
heavy fuel oil integrated gasification cc turbine	1806	1806	28	28	1.00	35	30	60
natural gas gas turbine combustion	765	765	6	6	1.12	35	40	85
natural gas combined cycle gas turbine	1402	1402	7	7	0.65	35	97	85

A.2.6.1 Availability factors of renewable energy

The availability factors (AF) are summarised in Table A5 and illustrated in Fig. A6, A7 and A8. This variability was taken into account adding additional constraints to the penetration of variable renewable energy technologies. The calculations are documented for transparency purposes in ref (Astudillo 2017).

Table A5: availability factors of different renewable energy sources

Daily	FD	FN	FP1	FP2	RD	RN	RP1	RP2	SD	SN	SP1	SP2	WD	WN	WP1	WP2
Wind	0.42	0.44	0.45	0.36	0.33	0.36	0.42	0.31	0.31	0.36	0.41	0.29	0.39	0.41	0.42	0.34
Solar	0.34	0.00	0.11	0.09	0.37	0.00	0.10	0.10	0.45	0.00	0.23	0.22	0.20	0.00	0.01	0.00
Run of river	0.57	0.57	0.57	0.57	0.62	0.62	0.62	0.62	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Seasonal				fall				spring				summer				winter
Run of river				0.57				0.62				0.57				0.57
Annual																
Run of river																0.53
Dam hydro																0.53

The first letter of the time slice code indicates the season (F: fall, R: spring, S: summer, W: winter), the second the fraction of the day (D: 9am-4pm, N: 8pm-5am, P1: 6am-8am, P2: 5pm-7pm).

A.2.6.2 Hydropower availability factors

Run-of-river availability factors by season were estimated from the amount of water circulating by representative run-of-river plants in Quebec (Dataset E). Winter flows are not the lowest (as would be expected in natural flows) since they are influenced by upstream reservoirs, which store energy to surpass the winter peak demand. We considered that the seasonal AF of run-of-river would be at least as high as during the winter season, the period further away from spring, which is the period of maximum runoff. The maximum annual AF is estimated based on the annual average ratios of electricity production to nameplate capacity of hydropower in Quebec (Fig. A7).

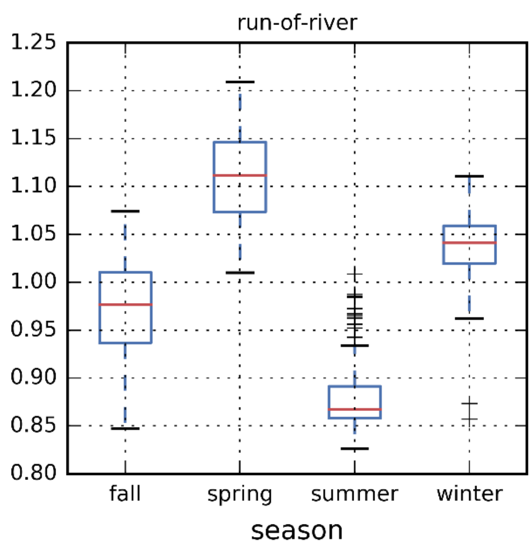

Figure A6: Boxplot of the proxy of power generation in run-of-river power plants in Quebec – grouped by season and normalised by annual generation. From dataset E.

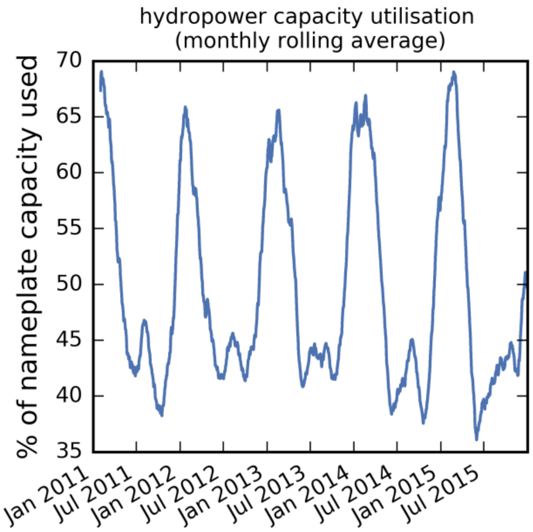

Figure A7: % of capacity utilisation of hydro power in Quebec (2011-2015) (monthly rolling average). From dataset B

A.2.6.3 Wind availability factors

This study uses the data made available by the Canadian Wind Energy Association (CanWEA) in their Pan-Canadian wind integration study (Canwea 2016). The data includes projections of wind production per hour for 4984 sites in Canada, 1382 in Quebec. Different sites are used to evaluate various levels of wind power penetration. For consistency, we used just the sites included in the 35% wind power penetration scenario, which was chosen as maximum yearly penetration levels.

Since we were not interested in intra-site variability, the production data by site was aggregated to have a regional estimate. The three years of production were averaged to model a representative dataset of annual wind production from new wind sites in Quebec. The availability factors per time slice were calculated normalising the data, so the annual average coincides with the values summarised in the metadata provided by CanWEA (Astudillo 2017).

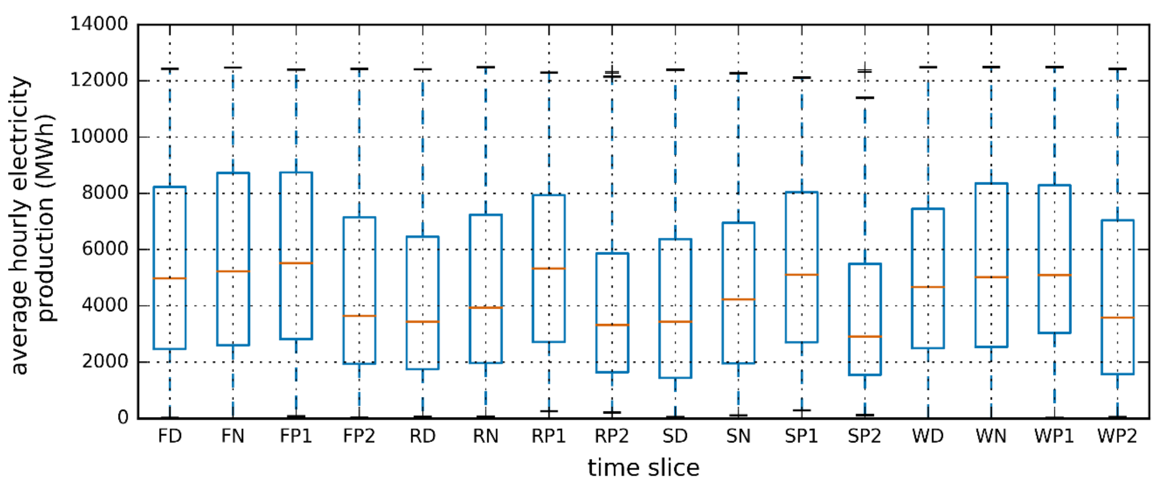

Figure A8: Boxplot of Simulated electricity production from representative wind power plants in Quebec grouped by time slice.

Production of years 2008-2010 were averaged to represent an average year. Calculated from dataset F. The first letter of the time slice code represents the season (F: fall, R: spring, S: summer, W: winter), The second the fraction of the day (D: 9am-4pm ,N: 8pm-5am , P1:6am-8am , P2:5pm-7pm).

A.2.6.4 Solar availability factors

The solar availability factors per time slice were calculated from the Canadian weather energy and Engineering datasets (SWEEDS) (Govt. of Canada 2016c). These datasets provide average solar irradiation data for different locations across the country. The distribution of the AF per time slice was assumed to follow the distribution of solar irradiation of these datasets. Solar irradiation was normalised and multiplied by the solar AF estimated in the Trottier Energy Futures project (Trottier energy futures project 2016). With the transformation, the annual weighted average of AF is equal to the annual values provided by the Trottier Energy Futures project.

A.2.6.5 Electricity trade

We considered that for energy security reasons, the percentage of electricity coming from imports during peak load and across the year would not change substantially. Dataset B was used to derive the maximum and average % of electricity supply coming from imports per day. We imposed a limit of 45% of electricity from imports per time slice. This level corresponds to the maximum penetration reached during several years (Fig. A9).

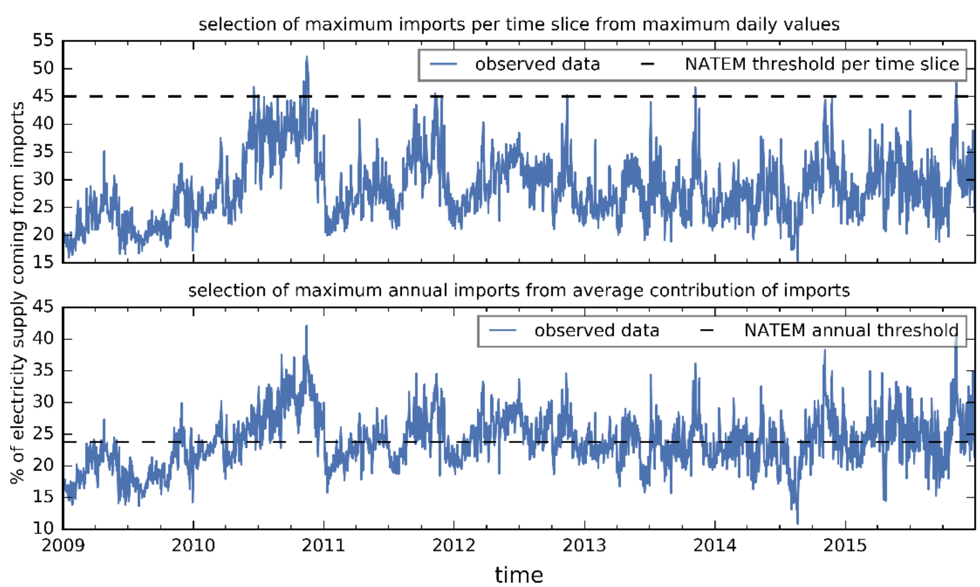

Figure A9: % of electricity supply in Quebec coming from imports (daily averages and maximums) 2009-2015.

The dashed lines indicate the thresholds set in NATEM for the maximum contribution of imports to electricity supply per year and time slice. Based dataset B.

We imposed a maximum annual share of 24% of imports, which correspond to the average contribution of imports (2009-2015).

A.3 Additional results

Table A6: Main contributors to GHGe in 2050 (GHG50 scenario)

Technology	Contribution to total CO_{2eq} in 2050	sector
Maritime transport (generic)	12.9%	Transport
“Other manufacturing” industries (natural gas use)	11.5%	Industry
Transport off-road (generic)	6.1%	Transport
Light freight trucks (gasoline cfv)	5.2%	Transport
Air transport passenger international	4.3%	Transport
Aluminium industry (coal use)	3.9%	Industry
“Other industries” (diesel consumption)	3.9%	Industry
Chemical industry (natural gas use)	3.8%	Industry
Refinery industry	3.5%	Industry
Iron and steel (natural gas use)	3.4%	Industry
Freight transport (heavy diesel trucks)	3.1%	Transport
Aluminium industry (natural gas use)	3.0%	Industry
Commercial sector (other services)	2.8%	Commercial
Air passenger transport (domestic)	2.6%	Transport
Pulp & paper industry (natural gas use)	2.2%	Industry
Other mining industries (Heavy fuel oil use)	2.0%	Industry
Cement production industry (coal use)	2.0%	Industry
Hybrid small passenger car (gasoline)	1.8%	Transport
Hybrid large passenger car (gasoline)	1.7%	Transport
Other manufacturing industries (natural gas use)	1.5%	Industry

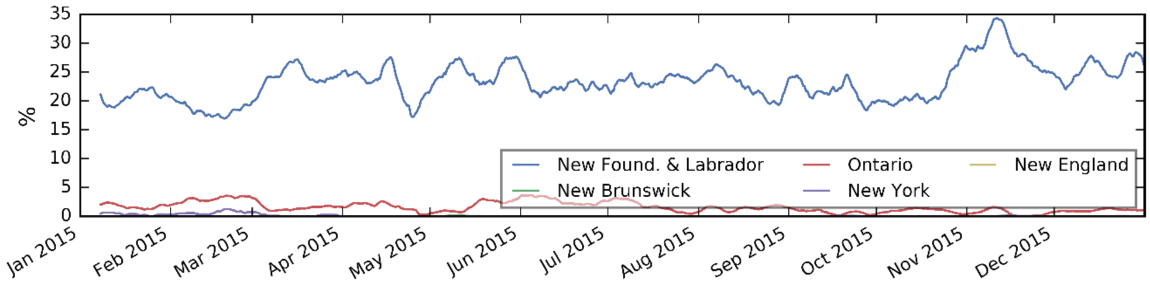

Figure A10: Contribution of imports to electricity supply in Quebec, disaggregated by exporting region. (Weekly rolling average of 2015).
Derived from Dataset C.

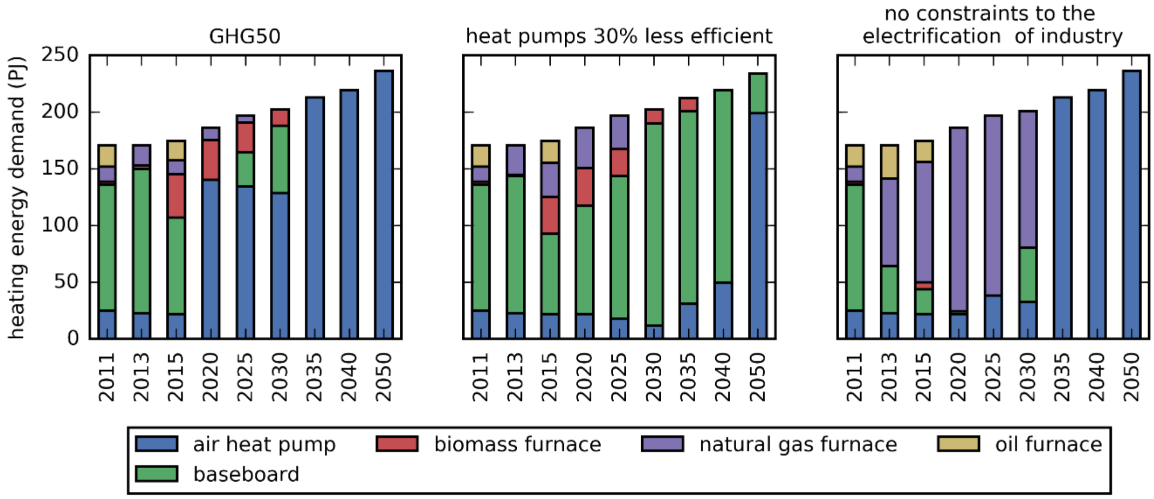

Figure A11: Cost-optimal technology mix of household heating technologies in Quebec (2011-2050) (GHG50 vs additional sensitivity scenarios).

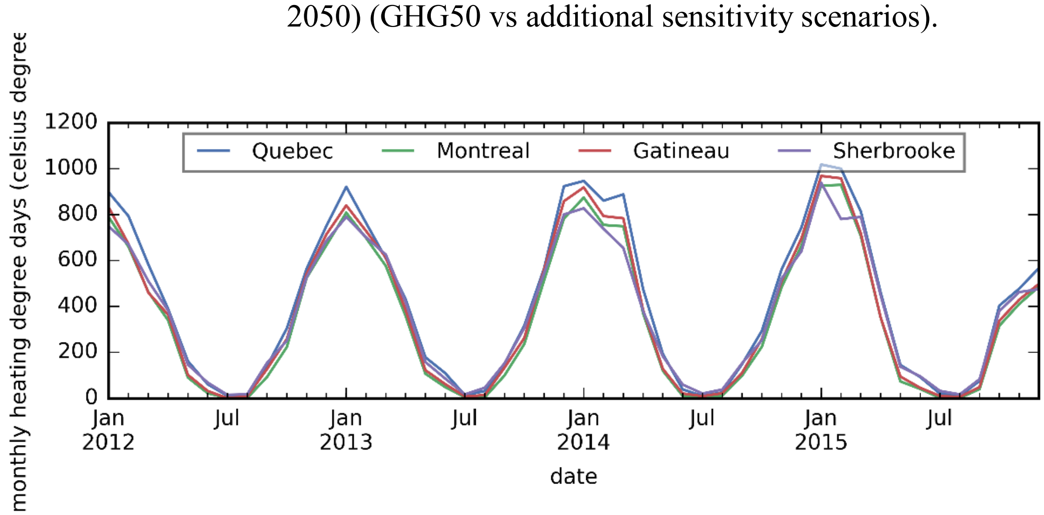

Figure A12: Geographical variability of heat demand. Monthly heating degree-days in the four biggest cities in Quebec (2012-2015)

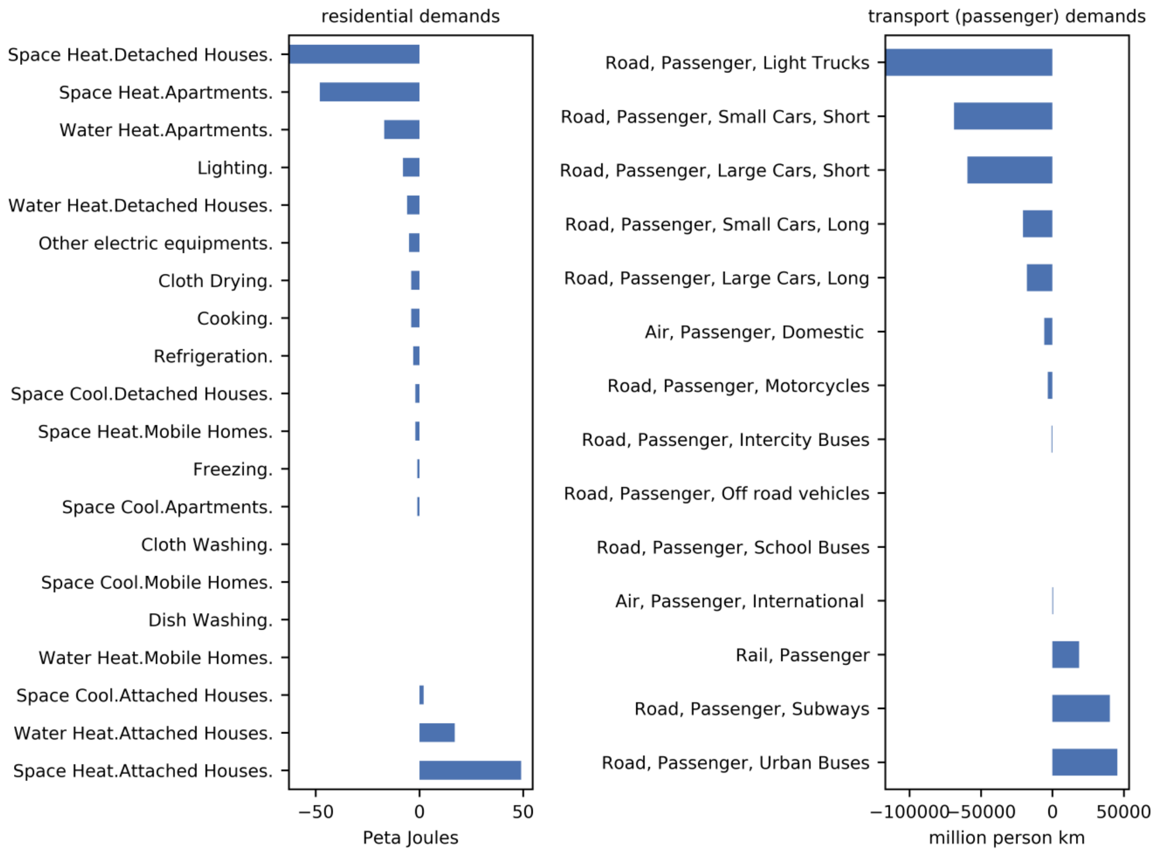

Figure A13: Main changes in demand of energy services in the Impr.Urban scenario with respect to GHG50 scenario (2011-2050)

Annex B: Supplementary material chapter 6

Electronic notebooks documenting the whole integration process are available for review at the open sicence framework website. The link is for reviewers only and not yet in the public domain, as the manuscript is still under review. https://osf.io/w94xr/?view_only=81ac50b2bb784542b70926abfd0e56b6

B.1 Review of the literature on the integration of LCA and ESOM.

Number of technologies mapped: Only two studies established an equivalent for all the technologies (i.e. complete mapping) in the ESOM (Menten et al. 2015; Rauner and Budzinski 2017) and it was for simplified models, with less than 200 technologies. Several of the studies based on input-output approaches matched a larger number of technologies (Daly et al. 2015; McDowall et al. 2018) using on sector resemblance and acknowledged that this approach erodes representativeness.

Several studies limited the number of technologies to be mapped considering fewer sectors than those included in the original model. A majority of studies focused on the electricity sector. Limiting the boundaries of the system under study to a subcomponent of a wider model would miss all the effects occurring outside the sector under study, despite all being interconnected by energy vectors. It is especially unwarranted when analysing the effects of changes in the system, what is known as consequential assessments (CLCA) in the LCA literature. It is also problematic when LCA results are integrated into the optimisation problem, as it produces biased models. The studies that introduced LCA coefficients but only for certain sectors acknowledge that this produces biased models whose results should be carefully interpreted (Daly et al. 2015; Pehl et al. 2017; McDowall et al. 2018). Moreover, addressing key policies, such as electrification of transport and heat services requires multisectoral approaches (Rauner and Budzinski 2017). It means also means "loosing" the strength of large multisector models.

LCA Scope: most of the studies are attributional (ALCA), and there are very few consequential ones (CLCA). However, the distinction is rarely stated and has been inferred from the objective and methodological approaches. Some of the CLCA assume that the use of TIMES model is inherently consequential (García-Gusano et al. 2016a) because system expansion is used to deal with multifunctional processes inside the regions under study. However, what is important is how the allocation is solved when it cannot be avoided, for example with processes where only some co-products are outside the system boundary. A practical example is the expansion of second-generation biofuel based on residues. In CLCA versions of ecoinvent, by-products are considered to be constrained. Hence a rise in production cannot be based on co-products. Thus, the use of an attributional database on a consequential assessment wrongly assumes the expansion of production from by-products is a possibility.

Parameter harmonisation: Several of the previous studies have done harmonisation of ESOM and LCA parameters either at inventory or impact score level. However, the effect of harmonisation has not yet been assessed. Efficiencies appear to have been only adapted in one study and at impact score level (Volkart et al. 2018), which implies the assumption that the impact of a given technology is directly proportional to its efficiency. Harmonising at score levels means contribution analyses using the LCA matrix formulation cannot be done.

Fuel switching: An additional difficulty is how to model changes in fuel mixes. Many of the promising technologies to reduce GHG emissions involve using biofuels or hybrid electric powertrains. Taking these changes into consideration requires procedures to add new fuels and modify emissions accordingly. To the best of our knowledge, such a procedure has not yet been addressed in the literature.

Reproducibility and documentation: There is substantial room for improvement on how the integration studies are documented (Vandepaer and Gibon 2018). Integration procedures should be unambiguously described, ideally "codified" in a software program so they can be analysed, reproduced and reused (Sandve et al. 2013). Some good examples include the work of Rauner and Budzinski (2017) and Mendoza-Beltran et al. (2018)

Table B1: Summary of studies integrating LCA with energy system optimisation models

Ref.	Model scope	Sectors considered	N tech. mapped	Model	Model paradigm	harmonisation	LCA Scope
(Hertwich et al. 2015)	Multisector	Electricity	21 tech x 9 regions	WEM	Simulation & bottom-up ESOM	CF from WEM	ALCA
(Gibon et al. 2017)							ALCA
(Berrill et al. 2016)	Electricity	Electricity	21	REMix	Bottom-up ESOM	CF and lifetime from REMix	ALCA
(Pehl et al. 2017)	Multisector	Electricity	11 tech. x 11 regions	REMIND	Hard-linked bottom-up ESOM and macro-economic optimisation	CF, CO_2 EF and lifetime	ALCA
(Menten et al. 2015)	Multisector	Multisector	192	MIRET	Bottom-up ESOM (TIMES)	Not done	CLCA
(García-Gusan	Multis	Electricity	36	TIMES-SPAIN	Bottom-up ESOM (TIMES)	Not done	

o et al. 2016a)	ect or						
(Volkart et al. 2017)	Multisector	Multisector	43	Swiss – Markal	Bottom-up ESOM (TIMES)	Partial, based on other prospective LCI.	ALCA
(Volkart et al. 2018)	Multisector	Multisector	203	Global Multi-regional Markal	Bottom-up ESOM (Markal)	Indicators scaled to consider efficiency differences	ALCA
(McDowall et al. 2018)	Multisector	Electricity	15	ETM-UCL	Bottom-up ESOM (TIMES)	Not done	ALCA
(Daly et al. 2015)	Multisector	Electricity	250	UK-TIMES	Bottom-up ESOM (TIMES)	Not done	ALCA
(Rauner and Budzinski 2017)	Electricity	Electricity	18	MOrOSA	Multi-objective optimisation	EF	ALCA

CF: capacity factors, EF: emission factors

B.2 Methods

B.2.1 NATEM – Quebec

This section presents the most recent updates from the version presented in Astudillo et al. (2017b) and extends the documentation.

B.2.1.1 Energy balance

NATEM is calibrated using the National Energy use database (NRCan 2013) to ensure coherence with national statistics. The NEUD relies heavily on the report on energy supply and demand (RESD) (Statistics Canada 2014) among other sources. The NEUD provides values of energy use by fuel and by end-use, grouped by sector for each Canadian province. During calibration, the energy by end-use is disaggregated by technologies that provide those services using the stocks of each technology and explanatory variables such as efficiency. The calibration process allows characterizing current technologies with parameters related to their use (e.g. passengers per vehicle) and their efficiency (e.g. MJ of fuel per km). The parameters related to the use of technologies are kept constant during the whole simulation period.

The calibration is done in a way that the energy consumption and delivery of energy services in the year of reference in NATEM match the values of the NEUD. For coherence, we use the fuel properties reported in RESD. Biodiesel and ethanol are not reported in the RESD, and higher heating values of 35.82 and 23.49 MJ/l were considered.

B.2.1.2 Greenhouse gas emissions balance

GHG of fuel combustion are a function of the amount of fuel consumed and the emission factor (EF), that is, the amount of emissions per unit of fuel combusted. NATEM accounts for the CO_2, CH_4 and N_2O emissions from combustion. The EFs per unit of fuel use are derived from the National Inventory Report (NIR) on GHGe, which relies on the RESD for the energy commodities. The consistency of sources ensures a consistent accounting of GHG from energy commodities across the country and provinces. NIR considers different emission factors depending on the sector, as characteristics of fuel and combustion units vary. The CO_2 EF and CH4 EF of transport have been updated for this study to the latest version of the report (Environment Canada 2017).

For fuels that are not covered in the inventory (wood pellets and biogas), EFs are derived from the LCA database ecoinvent (v3.5) (Wernet et al. 2015). CH_4 and N_2O emissions from solid biomass in the NIR inventory (table A6-34) are very high, around 22 g CO_{2eq}/MJ_{LHV} biomass, 25% of the CO_2 emissions of light fuel oil. The NIR EFs for biomass are based on a report from 2006 and are most likely outdated. Stoves built in 2004 had already emissions one order of magnitude lower (Johansson et al. 2004). Therefore we used values from the ecoinvent database, which are more in line with current wood stoves. Like in many other studies, "biogenic" CO_2 is assumed to have a global warming potential (GWP) of 0 (carbon neutrality assumption). While there is some delay in time between the absorption and release of bioderived CO_2, this period is very low in comparison with the residence time of CO_2 in the atmosphere.

Table B2: Sources of CH_4 and N_2O EF of biofuel combustion by sector

Fuel	Ecoinvent process	NATEM sectors
Biomass burning (small scale)	heat production, mixed logs, at wood heater 6kW, state-of-the-art 2014	Residential
Biomass burning (large scale)	heat production, mixed logs, at furnace 100kW, state-of-the-art 2014	Electricity, industry, commercial, agriculture
Wood pellets (small scale)	heat production, wood pellet, at furnace 9kW, state-of-the-art 2014	Residential
Wood pellets (large scale)	heat production, wood pellet, at furnace 300kW, state-of-the-art 2014	Electricity, fuel supply

biogas	biogas, burned in micro gas turbine 100kWe	Electricity, residential, commercial,

To have coherent global warming mitigation pathways, aggregated CO_{2eq} emissions for the reference year should be similar to emissions reported by the regions under study. The emissions included in NATEM correspond to the CO_2, CH_4 and N_2O emissions from stationary and transport fuel combustion as reported in the NIR. The total GHGs in the model are 58806 kt CO_{2eq} in 2011, 1.3% lower than the reported emissions from Quebec in the same year (Environment Canada 2017).. The discrepancy is low and considered valid. Differences could be due to slightly different EF for bio-derived fuels.

B.2.1.3 Main scenarios

The study compares two scenarios, one with and one without GHG mitigation targets. GHG mitigation targets in the model are of 37.5% reduction by 2030 and 70% for 2050 with respect to 1990 levels, using linear interpolation to set up constraints for intermediate years. Provincial governments have an identical mitigation target for 2030, but higher (80%) for 2050. As explained in previous studies (Astudillo et al. 2017b; Vaillancourt et al. 2017) the 80% mitigation target is not possible to achieve with the pool of technologies and constraints available in NATEM without changes in demand. Fig. B7 represents the GHG constraints per year compared with CO_{2eq} emissions in 1990.

We note that emissions in 2011 were reported using GWP of the IPCC 4th assessment report, while the constraints for the future use GWP of the 5th assessment report. The updated GWP are slightly higher for methane and lower for N_2O. Nonetheless, combustion emissions are overwhelmingly dominated by CO_2, thus the differences in CH_4 and N_2O EFs are not expected to have a significant effect on the results.

B.2.1.4 Update of the transport sector

Previous work underlined the importance of the transport sector in the decarbonisation of Quebec energy system (Astudillo et al. 2017b). Early iterations of the model also showed the relevance of the transport sector in GHG reduction. In this study, the modelling of the transport sector has been revised and actualised to provide a more robust assessment of the mitigation options. Since this study does not consider modal shifts, the focus has been on the technologies that consume most of the energy (Fig. B1) (i.e. intra-modal improvements).

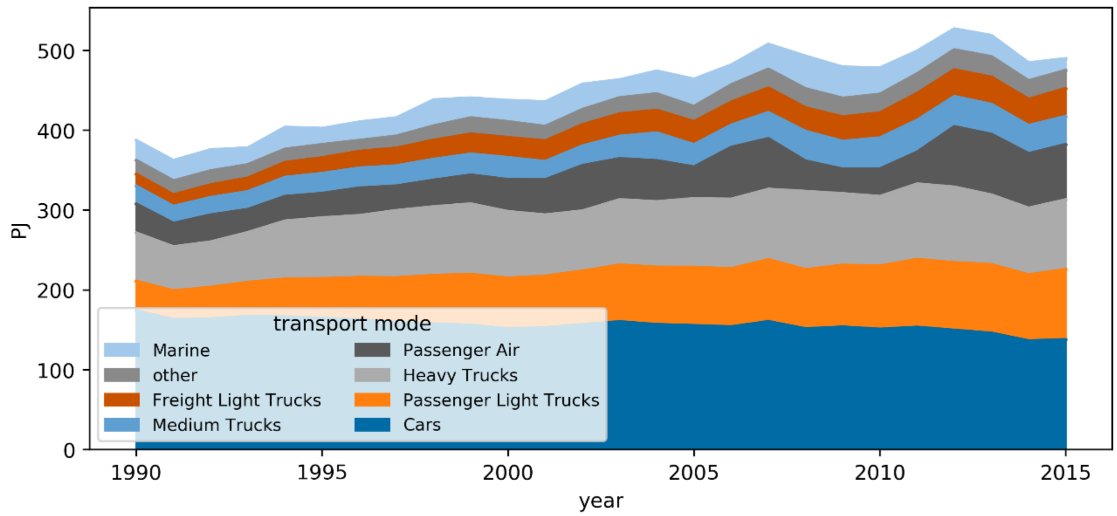

Figure B1: Energy consumption per transport mode in Quebec (1990-2015). The category "other" groups all the modes that contributed less than 2% to the total energy consumption.

B.2.1.5 Existing technologies

The NATEM model is calibrated with statistics from the Canadian government (NRCan 2013; Statistics Canada 2014; Environment Canada 2017). Aggregated data on fuel consumption by sector is reconciled with data on kilometrage, fuel consumption and stock to estimate the average load of different transport options. The load of a given energy service (i.e. average number of passengers or tonnes per vehicle) is estimated as the annual aggregated activity divided by the annual average distance travelled and kept constant during the whole period.

The average fuel consumption is derived from the average fuel consumption (NRCan 2013), converted to fuel consumption per unit of energy using HHV of the RESD report. Biofuels are assumed to have the same efficiency per unit of energy that the fossil fuel counterparts but their lower HHV is considered in the estimation of fuel consumption.

B.2.1.6 New technologies

Powertrains

With respect to previous versions of NATEM (Astudillo et al. 2017b; Vaillancourt et al. 2017) the heavy, medium and light freight, small car, large car, light passenger truck and urban buses have been updated. These technologies are the most energy-consuming, and therefore a priority for GHG mitigation. Table B3 details the powertrains that have been considered in road transport

Table B3: Powertrains considered in different road transport segments.

	Heavy freight	Medium freight	Light freight	Small car	Large car	SUV	Urban bus
ice-ci	■	■	■	■	■	■	■
ice-si			■	■	■	■	■

ice-cng-si							
ice-ngl-ci							
Hybrid si							
Hybrid ci							
Plug-in si							
Plug-in ci							
Battery							
cat-ers							

ice: internal combustion engine, si: spark ignition, ci: compression ignition

Efficiency and costs

Cars

In NATEM the passenger transport market is segmented in small cars, large cars and light trucks (i.e. SUV). The small and large car can provide long and short distance travel services. The efficiencies and costs of the technologies are based on data from the THELMA project (Bauer et al. 2015, 2016), which assessed efficiencies and costs of current and future passenger transport powertrains under different driving cycles. The Thelma project estimated current and future efficiencies using backward facing simulation, that is, deducing the energy needs required to have a given speed profile. The analysis considered the principal forces involved in car dynamics (e.g. aerodynamic drag and rolling resistance) as well as the estimates of weight reduction over time. The technical details are provided in the final report of the Thelma project (Bauer et al. 2016). The short distance energy consumption was estimated with the urban cycle and the long distance with the highway cycle as modelled in the THELMA project, which is based in the *worldwide harmonized light vehicles test procedure* (WLTP).

The matching between the technologies described in Thelma and those in NATEM required the following assumptions:

- Engines using ethanol are assumed to have the same efficiency[5] than gasoline engines.
- Engines using biodiesel are assumed to have the same efficiency than diesel cars.
- GPL cars are assumed to have the same efficiency as CNG cars.

[5] Efficiency measured in distance travelled per unit of energy. Biofuels have a lower heating value hence efficiencies per unit of volume are larger than for conventional fuels.

- Small cars (gross weight <1182 kg) approximated by the categories *mini* (830 kg s= 80 kg) and *small* (988 kg, s=96 kg).
- Large cars (gross weight > 1182 kg) are approximated by the categories low-midsize (1191 kg, s=119), midsize (1371 kg, s=142) and up-midsize (1786 kg, s= 164 kg).
- Passenger light trucks are approximated by the cars in the category *SUV*.

Buses

Efficiency improvements for buses with different powertrains are derived from Cox et al. (2017) using the maxi-bus as the most suitable proxy (Cox, pers. Comm).

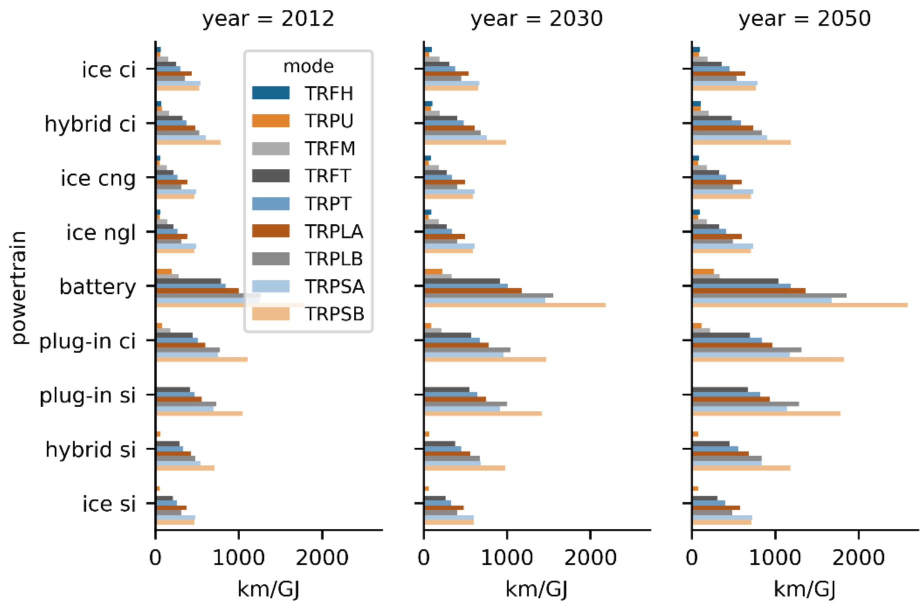

Figure B2: Efficiency of road vehicles per powertrain and year.

Ice: internal combustion engine, ci: compression ignition, si: spark ignition, cng: compressed natural gas. TRFH: heavy truck freight, TRPU: bus, TRFM: medium truck freight , TRFT: light truck freight, TRPT: light truck passenger , TRPLA: large car long-distance, TRPLB: large car short distance, TRPSA: small car long-distance, TRPSB: small car short distance.

Freight transport

Freight road transport is considerably more complicated to model than passenger transport since much less data is available. For medium and heavy freight, efficiencies and costs come from a variety of sources (den Boer et al. 2013; IEA 2017; Moultak et al. 2017). A spreadsheet in supplementary information documents the parameters. Electric road systems with catenaries are a promising technology (IEA 2017; Moultak et al. 2017), and here it is modelled as one of the alternative options. To our knowledge, this is one of the first assessments with ESOM considering this technology.

Light freight trucks have been modelled as light passenger trucks adapting fuel consumption due to higher loads. The increase of fuel consumption due to increased weight has been extrapolated using linear regression from THELMA data. The relation between energy use and total mass for the different powertrains and years is displayed in Fig. B3.

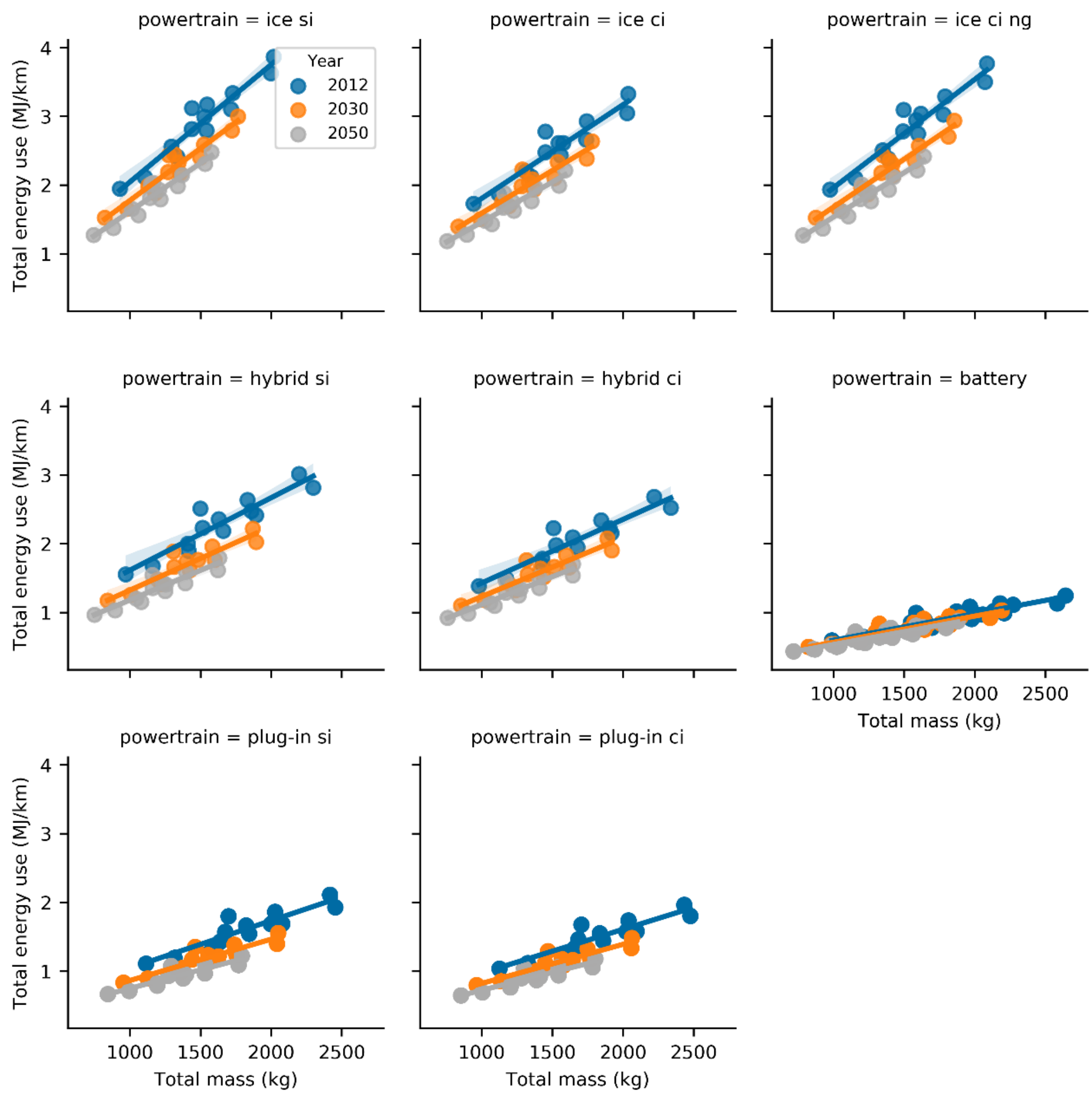

Figure B3: linear extrapolation of fuel consumption per powertrain as a function of weight.

si: spark ignition, ci: compression ignition. Data derived from the THELMA project.

Airplanes

The efficiency of future passenger aircrafts is calculated from a recent prospective analysis of the Swiss commercial fleet (Cox et al. 2018). Fuel consumption has a strong non-linear relationship with flight distance (Cox et al. 2018). Hence average distance is an essential factor in the characterisation of the efficiency, particularly for short flights. For domestic flights efficiencies are based on the average distance of domestic flights in Canada (450km) (Statistics Canada, Pers. Comm.) For international flights, an average distance of 3000 km was assumed. Calculations are detailed on notebook 7.

B.2.1.7 Optimisation constraints

Constraints are used to represent technical or policy limitations to the space of potential solutions. We chose to limit constraints to the minimum, so results can be more easily interpreted. This means we do not introduce constraints to try to replicate non-optimising behaviour.

Transport

- Electric road systems are assumed to be viable only for 30% of the road heavy freight demand from 2030, as they are only cost-effective in routes with heavy traffic (IEA Future of trucks).
- Battery-based medium freight trucks are assumed to be viable for 30% of the traffic from 2030 when the technology becomes available.
- Battery electric cars can only cover 30% of the long-distance demand for passenger transport (small cars, large cars and light trucks).

Electricity (See Astudillo et al. (2017b) for details)

- The average and maximum share of annual electricity imports are assumed to do not increase above existing levels. This constraint represents energy security concerns (see Astudillo et al (2017b) for details.
- The maximum and average share of intermittent renewable energy is limited to represent grid stability requirements.
- The resources available for renewable energy are limited.

Industry and agriculture (See Astudillo et al. (2017b) for details)

Industry: The share of energy use in the form of electricity for each industrial sector is based on the maximum share of electrification of the same sector in other Canadian provinces. The minimum share of non-electric energy sources is fixed to 65% of the share at the start of the simulation period.

Agriculture: The minimum share of energy coming from electricity is constant during the simulation period. The minimum share of other energy sources for 2050 is fixed at 50% of their market share in 2011.

Total Greenhouse gas emissions

GHG mitigation targets in the GW mitigation scenario are of 37.5% reduction by 2030 and 70% for 2050 with respect to 1990 levels, using linear interpolation to set up constraints for intermediate years.

The effect of constraints in the model can be analysed by the shadow price. Apart from the apparent effects of the constraint on GHG, other constraints of the model are affecting the solution. Constraints to electrification of road transport limit rates of electrification and further studies to refine assumptions would be of interest, particularly, to what extent road freight can be electrified. Other relevant constraints are the rate of electrification for energy demands of the industrial sector. There is a lack of detail on the statistics of energy consumption of the industrial sector (Astudillo et al. 2017b) and this is hampering mitigation efforts.

B.2.2 Goal and scope

The formal definition of the study is framed using the “goal and scope” phase, the standard procedure used in LCA. The advantages of defining the study in a systematic manner using the “goal and scope” definition have also been recognised in the energy system model community (DeCarolis et al. 2017). The goal of this study is to formalise the methods needed to quantify the potential environmental impact of broad changes in the energy system particularly, how to use the results of ESOM together with LCA to improve data quality. A secondary goal is to derive lessons for the energy transition of the region under study: the province of Quebec.

Intended audience: The intended audience can be divided between those who work either in LCA or ESOM, and those outside these fields of expertise. The use of jargon is avoided as much as possible, but a substantial amount of prior knowledge is required not to misinterpret the results. Therefore, an effort is made to underline the rationale and limitations of both LCA and ESOM.

Functional unit: The function of the system under study is to provide energy services to the province of Quebec for the period 2011-2050. On aggregate they represent the energy needs as quantified by the official statistics. These services are quantified for 2011 and projected until 2050 based on a series of exogenously defined drivers. The services as defined are considered independent (e.g. bus transport cannot substitute car transport). The model includes elasticities to the prices of energy services, meaning that the demand is to some extent dependent on its cost. The potential effects of the GW mitigation policy are studied comparing two alternative scenarios which fulfil the same energy services but one with the policy and a counterfactual scenario without. The study follows the CLCA paradigm, where studies attempt to assess the effects of changes in the system. CLCA attributes all the burden of the changes in the system to the origin of the change.

The demand (vector of demand in LCA) is composed of all processes that deliver ‘final’ energy services (as opposed to intermediate flows) and are identified as relevant by the screening algorithm plus the consumption of ‘non-relevant’ processes, consuming a commodity whose market is deemed relevant by the screening process. In our case, the electricity consumption of all final demands is considered because there are substantial changes in electricity supply.

System boundary: In line with the scope, the study aims to capture the most critical changes in the system. It does so with the help of a partial equilibrium optimisation model of the TIMES framework, probably the most widely used general-purpose ESOM. the model is described in detail in previous sections and publications (Astudillo et al. 2017b). TIMES models the market clearance (matching of supply and demand) on a defined market for energy services. The partial-equilibrium assumption means that markets outside the energy system can supply goods but do not see their clearance affected by what happens inside the system. These markets are defined by background LCA databases. Ideally, they would represent how the markets react to a change in demand during the studied period (2011-2050). The consequential version of Ecoinvent v 3.5, models only existing production of goods and services and not future ones (Wernet et al. 2015). Thus, results from our approach are as if the "rest of the world" remains the same and as such should be interpreted.

Cut-off criterion: In theory, all the processes that change their production volume should be included in the analysis. However, since more than 600 processes change their emissions, we implement an screening algorithm to include only those that contribute the most to the absolute changes in CO_{2eq} emissions. The implementation reduces the number of processes exponentially to be considered, setting a balance between completeness and study feasibility. The procedure is documented in the electronic notebooks of the study, and it is the method we propose to simplify the mapping problem.

Allocation: How to allocate the burdens of multifunctional processes has long been debated in the LCA field. For processes within the energy system, allocation can be avoided by means of system expansion. Multifunctional processes, namely biodiesel and electricity autothermic gasification have to be simplified to single-output unit processes using an allocation factor. Nonetheless, the aggregated results, (i.e. the effects of the change under study) are independent of these factors since all the co-products are used within the system. However, care should be taken in the contribution analysis during the interpretation phase, since knowing the life cycle impact of a specific observation in NATEM (e.g. the increase in the electrification of cars) requires the use of allocation factors. Several transport processes provide long and short distance travel, which is also problematic to model in LCA. The results of NATEM take into account the different fuel efficiency and technical constraints between both services. However, for simplicity, the LCA component aggregates both long and short distance travel in one single transport service. The process delivering the aggregated service has an efficiency based on NATEM, reflecting the total distance and total fuel consumption. The study uses the consequential version of ecoinvent 3.5, which is consistent with the scope of the study: the effects of changes induced by the GW mitigation policy.

Data representativeness: We consider the data quality, as assessed in LCA (Astudillo et al. 2017a), to be adequate for a prospective analysis. Efficiencies and CO_2 emission factors for the main contributors are based on NATEM, which is more representative of future technologies than ecoinvent. The selection of suitable proxies from ecoinvent is based on name resemblance. Usually, the same process is available in different regions. Priority was given to the version of the region under study (Quebec). If it did no exist "Rest of the World" or "Global" datasets were chosen. We note that there can be substantial regional differences in the environmental impact of a product or service, depending on where it was generated. The harmonisation of parameters between the two models improves the consistency and representativeness of the model.

Efficiency values from NATEM are used to scale fuel use and airborne emissions. It is assumed that all airborne emissions of the adapted ecoinvent processes are due to fuel consumption. This is clearly the case for cars, where non-exhaust emissions are modelled separately (Simons 2016). For other processes we considered it to be a reasonable assumption.

Efficiencies of a process in TIMES are defined differently than in LCA. The same process can have efficiency improvements over time. Thus, efficiencies are scenario specific. Therefore, different versions of the same process exist, one for the business as usual scenario, and another for the GW mitigation scenario.

LCI Consistency: NATEM quantifies energy commodities in energy terms, while ecoinvent usually uses mass. Thus, heating values for fuels are used in the conversion. The current version of ecoinvent rarely references the heating value considered in each process. This study uses values reported in ecoinvent v2, from which most of the datasets are derived. In transport processes, the function can be expressed in pkm/Tkm or km. In cases where the definition differed between NATEM and ecoinvent, occupancy values of NATEM derived from the calibration were used. See notebook 1 for the details.

NATEM and ecoinvent model CO_2, CH_4 and N_2O emissions from combustion. CO_2 emissions are by far the most relevant emission from GW perspective (Fig. B4). Thus the harmonisation only affects CO_2 emission factors.

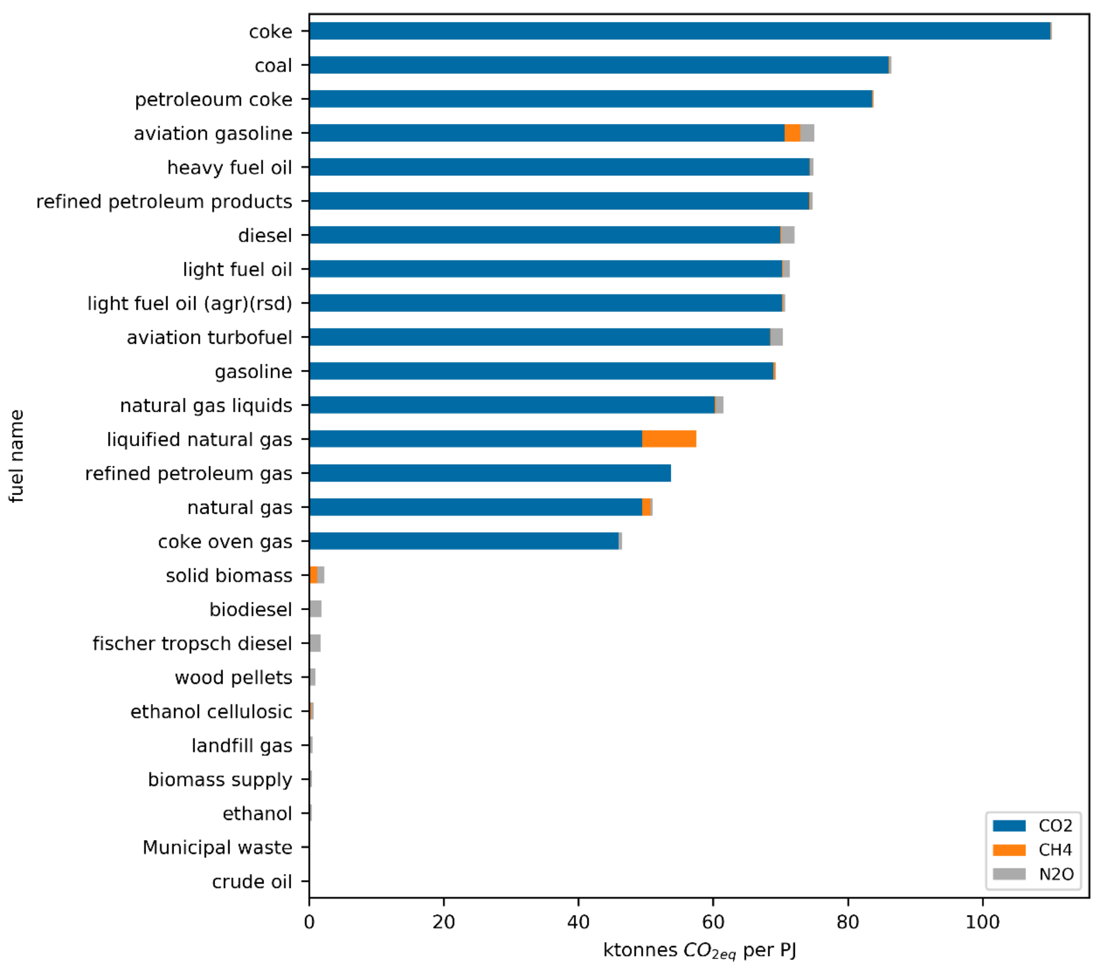

Figure B4: Combustion emission factors of fuels per unit of energy in CO_{2eq} units. Emission factors are averaged per sector. Some fuels are just present in specific sectors.

For processes using blends of fossil and bio-derived fuels, only the CO_2 emissions are adjusted, reducing the CO_2 emissions by the % of bio-derived fuels. CH_4 emissions in natural gas and liquified natural gas are particularly high in the transport sector, although the relation is not apparent due to sector-averaging. For emissions that are included in ecoinvent but not in NATEM, ecoinvent values are used.

LCI Completeness: The inventory includes many changes in different parts of the energy system foreseen by changes in the market, improving completeness. The data sources of the main contributing processes (e.g. transport), as well as emission factors, are documented. Transparency is improved by documenting the use of times2lca in electronic notebooks.

Some processes required specific adaptations. For instance, hybrid electric vehicles do not exist in ecoinvent. Values from THELMA and the literature were used to include battery needs on them. Conveniently, LCI of be cars is also based on THELMA (Del Duce et al. 2016), increasing consistency. Other processes did not exist in ecoinvent and were created from zero. For those, the inputs and emissions come from NATEM. The process is documented in notebook 3.

Impact assessment method: The study uses the impact assessment method Impact World +, the state of the art in LCA. The study report impacts to human health and ecosystem quality, referenced as "areas of protection" in the LCA literature (UNEP-SETAC 2016) as well as the contribution to different mechanisms to environmental damage. For specific flows which had a high contribution to impact scores and were occurring in a localised region, regional instead of global characterisation factors were used.

Impact World+ as well as alternative methods (Huijbregts et al. 2016) consider the impact of climate change in ecosystem quality and human health. For the calculation of CO_{2eq} emissions, global warming potentials developed by the IPCC were used. For consistency, we have chosen to keep the GWP of GHG as implemented by the ecoinvent database and LCA software such as Brightway2 (Mutel 2017) or Simapro. However, this implementation does not include the effect of climate change feedbacks, as recommended by the UNEP-SETAC initiative and the IPCC. The reason argued is that the feedbacks are only accounted for some GHG and consistency was preferred instead of precision. As far as CH_4 and N_2O are not significant contributors to the GHG budget, the differences in implementation of GWP are not likely to affect the results significantly.

B.2.3 Additional results

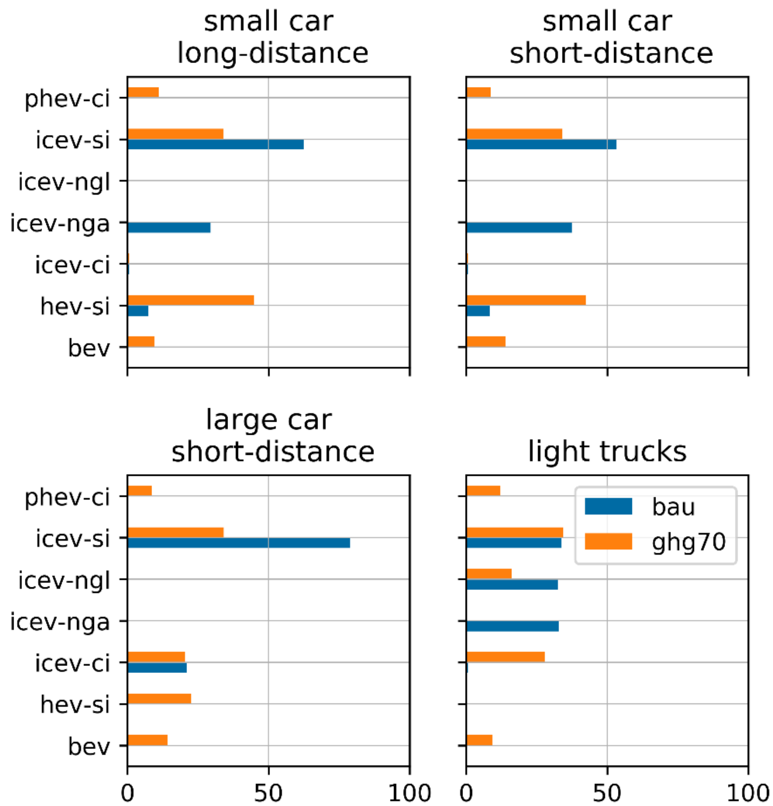

Figure B5: Average market shares in personal road transport (2011-2050) by scenario.

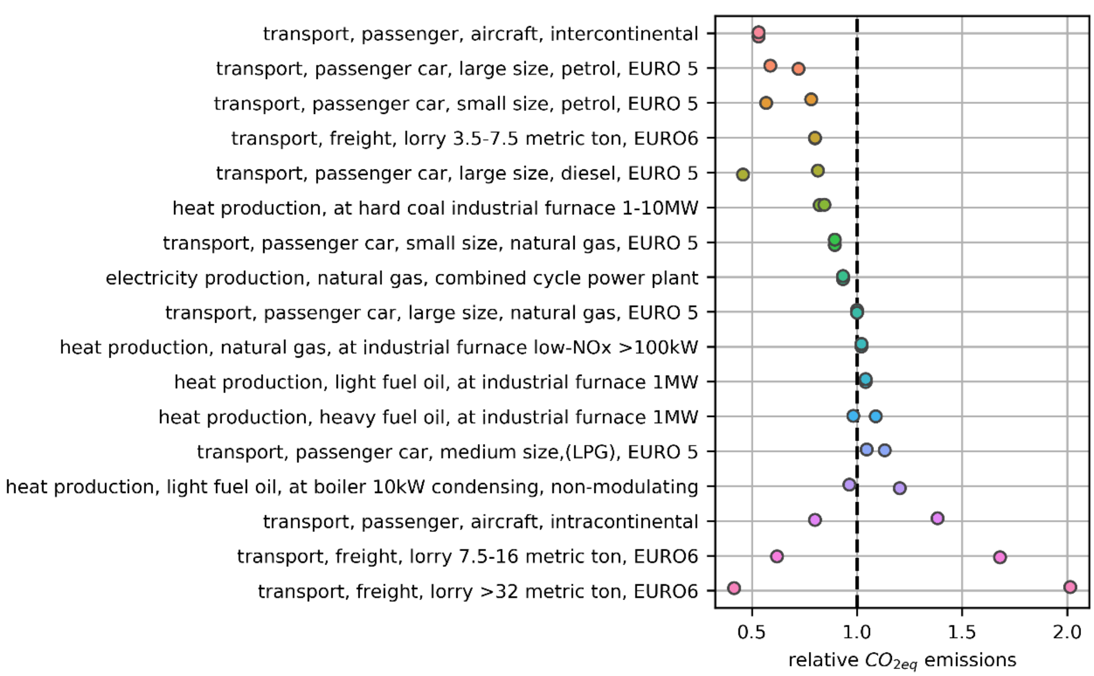

Figure B6: Effects of LCI adaptations on CO_{2eq} score (fuel efficiency, emission factors and fuel switching).

Fig. B6 represents the relative CO_{2eq} emissions between the final process and the initial proxy from ecoinvent, once the efficiency, emission factors and fuel mix is updated. Each proxy process is used at least two times (bau and mitigation scenario). In the higher end, much more efficient processes are found in vehicles with hybrid powertrains and airplanes. Hybrid vehicles are modelled from conventional ones, hence the difference in efficiency. For airplanes, the difference originates from fuel efficiency improvements in aviation.

In the lower end, heavy road freight diesel trucks are less efficient in NATEM. The differences in road freight are due to the low payloads result from the calibration. The low payloads are the consequence of an underestimation of freight service demand (MTkm) in the NEUD database (NRCan 2013). Activity levels are based on a subset of the road freight sector (CANSIM Table 403-0004), which only partially covers the heavy freight activity. We decided not to modify payloads, because the final demand of freight truck is also based in the activity estimates. Hence results are overall correct. This example highlights how soft-linking can help to improve the quality of both models.

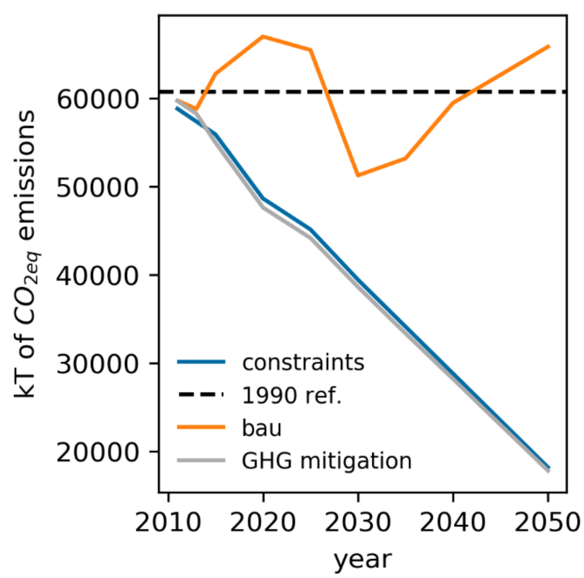

Figure B7: NATEM CO_{2eq} emissions per scenario

In the BAU scenario, there are some emission reductions that occur purely by economic reasons. They are mainly driven by the introduction of road freight electric road systems and the substitution of heating oil by electric heating in commercial and residential sectors.

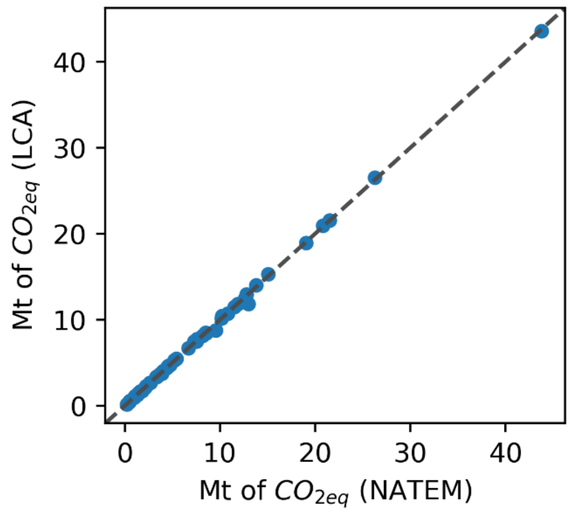

Figure B8 Use-phase CO_{2eq} emissions per process: comparison of NATEM and integrated model.

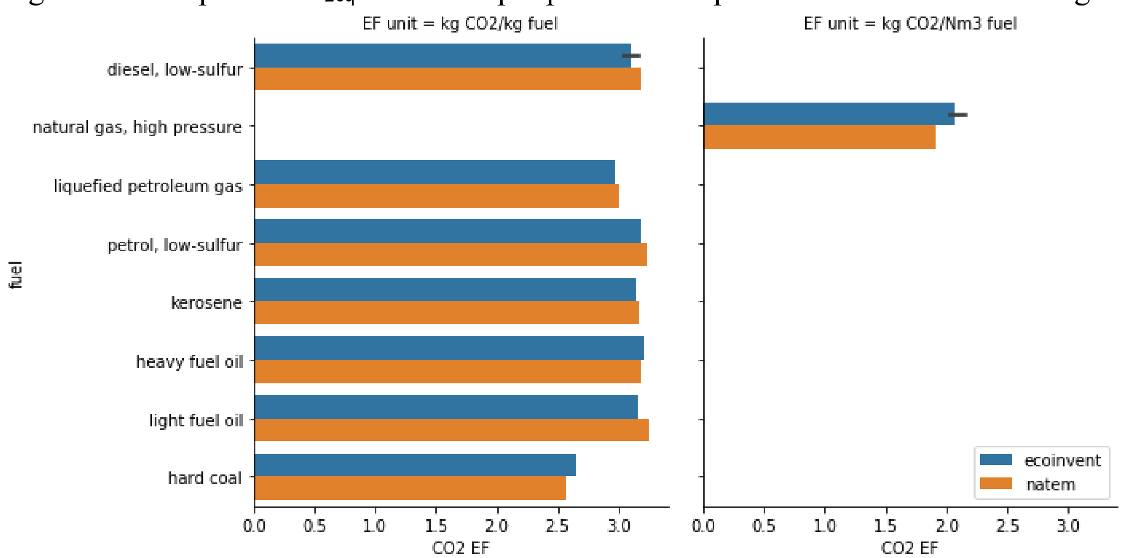

Figure B9: Comparison of combustion emission factors in the LCA database and NATEM.

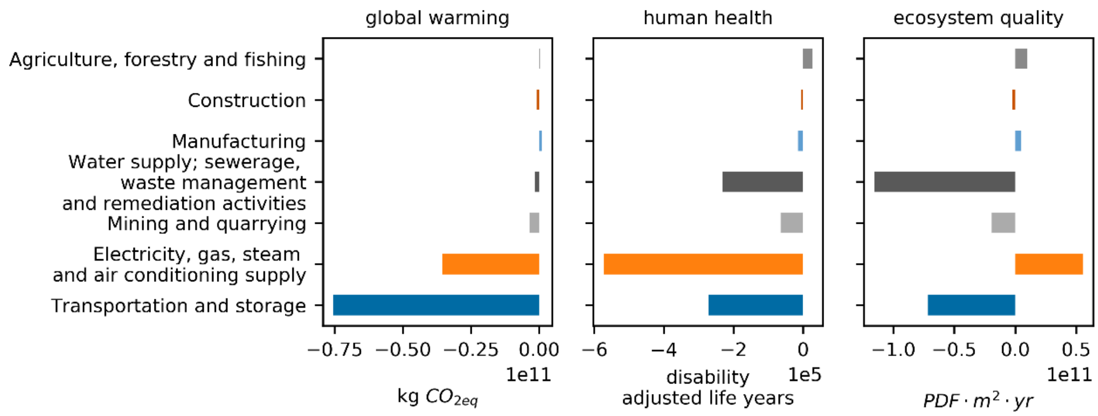

Figure B10: Environmental impact by sector. Grouped according to the divisions of the international Standard classification of all economic activities (isic codes).